Terrestrial laser scanning for detection of tectonically induced slope processes

Final Report

2008-2012

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with contributions of

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Final Progress Report (2008-2012) of Project *Terrestrial laser scanning for detection of tectonically induced slope processes*

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This project was financed by the *Austrian Academy of Sciences* in the framework of "*Geophysics of the Earth's Crust*".

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Preface

A picturesque, geographically surprisingly elongated Western Austrian settlement on the hillside of the Bregenzer Alps: that is Doren, the locality of an exciting and, at the same time, endangering geoscientific process, on-going landsliding. The interplay of the postglacial surface evolution, the erosional activity of the Weißach river, and the tectonic and sedimentological setting of the underlying strata form a (fortunately) almost unique phenomenon, a complex rotational landslide that is known to be active for at least two centuries.

Having been informed about the phenomenon in 2007 and having had the opportunity to visit the spectacular place just after a major activity in September of the same year, I personally became very much interested in this process. At that time, airborne laser scanning was already an established data acquisition method, and terrestrial laser scanning was about to be established in this field. Excited by the opportunity we wrote in the research proposal in 2008:

> *This pilot project aims at the possible application of Terrestrial Laser Scanning (TLS) in this area. In theory, TLS is applicable from one side to the other in alpine valleys if the two sides of a valley are not extremely far away (one to a few km). Other problems like uncooperative geomorphic setting should be overcome. Another issue is the presence of canopy cover that is not directed like in the case of ALS, but often obliquely. In this sense the canopy may also cover larger parts of the field of measurements. Finally, the targeted accuracy is at the limit of current technology and achieving cm-accuracy over large distances is a challenge with respect to instrumentation set-up and measurement configuration.*

That was very much true at that time, and now, after five years, we can state that TLS measurements became almost a standard method in landslide monitoring. As the whole community worldwide, we ourselves learned a lot as well about the method and about the phenomenon in this period of time.

I have been always excited to visit the place yearly and observe the man-made and natural changes, the development of geomorphic features of various scales, as well as the growth of the vegetation and the reshaping work of Weißach at the toe of the landslide. Each year I walked around the place; sometimes it was not a real walk due to the crisscrossed, fallen trees and dense shrubs. I became always astonished about the brute beauty of this helter-skelter of sediments, gravels, fallen wood, slippery ground, dropping water and muddy reaches, small and big holes and all this covered by various forms of life.

I hope the dear Reader can forgive me for these rather personal words; I just wanted to express how far I feel myself lucky to have had the opportunity to be part of this multidisciplinary research financed by the Austrian Academy of Sciences (ÖAW).

Although with this final report this era ends, nevertheless we plan to continue our activity in other forms. This document is intended as a rough overview what happened in the framework of the project. However, we intend to compile a more comprehensive volume about the results.

I hope the results we achieved and the data gathered during the project will be used by other researchers and will contribute to a deeper understanding of this phenomenon.

Vienna, 2013

Balázs Székely
(project initiator and report editor)

Contents

Introduction: The initial concept

Our project, *Terrestrial laser scanning for detection of tectonically induced slope processes*, has started in 2008 and is a part of the research and development activities of the Institute of Photogrammetry and Remote Sensing (IPF) of the Vienna University of Technology. A major research field of the institute is the application of various laser scanning technologies in science and engineering fields. The project is aimed at integration of problem-oriented development of data processing (in our case the natural hazards and neotectonics) with engineering-scientific objectives.

The long-term goals of our project can be summarized as

- multitemporal laser scanning data acquisition of numerous valley sides and steep slopes prone to potential landsliding and/or on-going tectonic activity in post-glacial Alpine tectonic settings.
- development and testing of co-registration and error analysis of long-range TLS (terrestrial laser scanning) data and comparison of derived DTM (digital terrain model) to DTM derivatives of ALS (Airborne Laser Scanning) data.
- development of field practices and data acquisition methods of georeferencing of TLS data in the long-range domain (e.g., with emplacement of retroreflecting objects as ground control points in the field).
- analysis of the effects of the presence of vegetation (primarily forests) on the oblique laser scanning acquisition setting.

In the research proposal the project was envisioned as a multitemporal, multi-site sequence of measurement campaigns focusing on various sites in the Federal State of Vorarlberg. This choice was made, despite the geographical distance from Vienna, because, unlike other Austrian federal states at that time, Vorarlberg had been covered wholly by good resolution airborne laser scanning already at the time of the project start; some areas were even scanned more than once. On the other hand, the geoscientific setting of the area (postglacial rebound, oversteepened valley sides, contrasting lithology, various types of mass movements at various scales) is ideal for monitoring and testing purposes.

According to the research proposal the project was planned for 3.5 years:

[Phase I]	*Initial phase*:	site selection, test measurements	1.5 years
[Phase R]	*Regular phase*:	regular measurements, data processing	1.5 years
[Phase E]	*End phase*:	continuation of regular measurements, preparation of publications and application for external (e.g., EU) financial resources	0.5 year

The total cost for the project was estimated to be: € 54250.-

The initial members of the research group were Dr. Gábor MOLNÁR, Andreas RONCAT, and Dr. Balázs SZÉKELY, led by Prof. Dr. Norbert PFEIFER as principal investigator. At the time of the project start all four researchers were employed at IPF.

The timeline of the project

The birth of the project

It happened in 2007 that Prof. Wolfgang WAGNER mentioned the possibility to study an active landslide at locality Doren (Vorarlberg). Since there was a planned meeting in Feldkirch in October, the possibility of visiting the site was realistic. Fortunately, our doctoral student, András ZÁMOLYI (Fig. 1) could be convinced to do some preliminary field work.

In the same days both Montafon valley and Doren could be visited. The latter was a lucky situation since in 2007 the landslide became active again, so the freshly uncovered surfaces could be observed.

The successful field work led to a project idea to study these phenomena with the help of terrestrial laser scanning. The actual call for proposal of the ÖAW seemed to be suitable to establish a project.

Fig. 1. The scarp and the freshly uncovered, unvegetated surface of the Doren landslide in October 2007. András ZÁMOLYI is standing on the steep slope showing the extent of the landslide. (View is to ENE. The picture was made during the preparatory field work.)

The call for proposal was a two-step process; first a letter of interest (LOI) should have been submitted. As our LOI proposal was found to be interesting in January 2008, we were asked to provide a more detailed project plan. The actual confirmation of the project happened in June 2008.

Division of the project activities

Instead of grouping the project activities into work packages, a logical categorization of the workload were sketched in the proposal (Phases I, R and E, see above).

The main activities of the project were:

- Initial preparatory activities (Phase I)
- Administrative tasks (Phases I, R & E)
- Field measurement campaigns (Phases I & R)
- Data processing (Phase R)
- Dissemination of results (Phase R & E)

Concerning the latter, the dissemination of results can be divided into two subgroups: oral and poster presentations at conferences (mostly Phase R) and publication of (written) scientific contributions (Phase E).

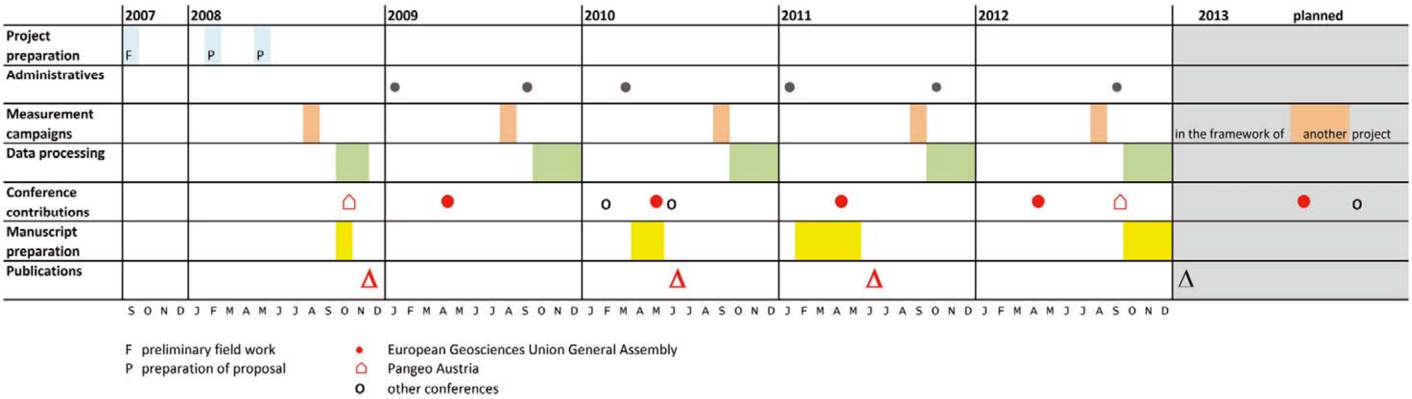


Fig. 2. The timeline of the project.

The original duration of the project was two years with the possibility for an extension. We applied for the extension, therefore the total time span of the project comprises the years 2008 to 2012.
As in the case of many projects, the eventual timeline (Fig. 2). and project structure differed from the planned schedule. As the gathered experience allowed, some intentional changes have been made in the activities and later in the focus of the research in order to reach the long-term goals of the project with higher reliability and more comprehensively.

Initial preparatory activities and first measurements (2008-2009)

The main goal of the activities of the year 2008 phase was the site selection and carrying out test measurements. According to the project concept during the Phase I two types of sites were expected to be selected. *Site Type A* where recently a large mass movement took place and it could be supposed that the material involved in

the movement was not completely settled yet, that is, soil creep or smaller dry or wet mass movements were expected to go on. *Site Type B* were those sites where oversteepened valley slopes were combined with talus/scree slopes and there could be some fluvial incision in the scree slope that potentially determined the movement/deformation of the scree slopes during or after increased precipitation events or snow melting.
In this year two areas were considered for site selection: locality Doren for Site Type A and the region of Montafon (southern Voralberg) for searching one or more suitable Sites Type B (see details in the next section).

In 2009 we continued to follow the same principle, so beside to scan the Doren landslide, suitable sites were searched in Montafon valley. Two slopes apparently affected by mass movements were selected, in both cases the highly unsorted tillite material is being eroded falling out in various quantities from the wall. These sites were situated in the Suggadinbach valley; their sizes were limited in order to be able to measure them in half a day.

Regular measurements at Doren (2010-2012)

As we gradually realized the major problem of the unsatisfying accuracy of co-georeferencing, we have given up Montafon sites in 2010, in order to be able to concentrate on the Doren site (Phase R). This measurement concept remained the same until the end of the project.
The new concept included the extended search for suitable station positions, extending the measured area, densifying the point cloud and increasing the point cloud overlap. Furthermore, we intended to increase the coverage of the toe of the landslide, because this part has been the most actively deforming part.
Parallel to this decision, we also extended the already started geological and geomorphological observations at and in the vicinity of the landslide.
These new goals were mostly achieved. However, the coverage of the toe varied considerably as many of the station points were washed away, destroyed by mass movements or became inaccessible. In these cases we had to repeat the search for suitable places accommodated to the new topographic situation.
The largest extent could be achieved in 2010. This year was very wet, consequently in the year many previous station points were not existing or measurable anymore. Especially the Krumbach side station points were affected. In finding the new station points another problem occurred: as the points had to be pulled back to the forested steep slope area, the GPS signal reception was very poor. In case of a few stations there were not enough retroreflectors visible in various directions, and therefore the georeferencing of these point clouds became very unstable. The main consequence was that, again, the most interesting parts of the toe of the landslide remained uncovered.

Data processing, methodological developments

The unsatisfying accuracy of the georeferencing of the point clouds led us to start development in the data processing techniques, refocusing our activities on the on the Doren landslide where the increase of accuracy and the visibility conditions were found most promising. First we considered these developments as improvements in processing techniques, but later on, as we were able to collect ancillary data, we realized that we actually need conceptual changes, consequently methodological developments.

The initial plan to simply compare the DTM surfaces generated from the yearly measurements was not feasible. The reasons for that are manifold:

- the most influencing factor is the difference in point cloud coverages of the subsequent years: often a well-covered area have to be compared to a low-point-density interpolated surface
- the differing point density is also related to the density of the vegetation: some points of the ground are resulted from a direct view measurement, whereas other points are partly reflected from the elements of the canopy cover (measured from a different station position) and they are difficult to filter out; these point groups are at slightly differing position in elevation, if the filtering is less successful, the resulting surface has a larger error
- even if we make use the full waveform technique, some points having increased two-way travel time (TWT) error (due to e.g. a plant), the final calculated position can be a decimeter away from the actual position (Fig. 3).

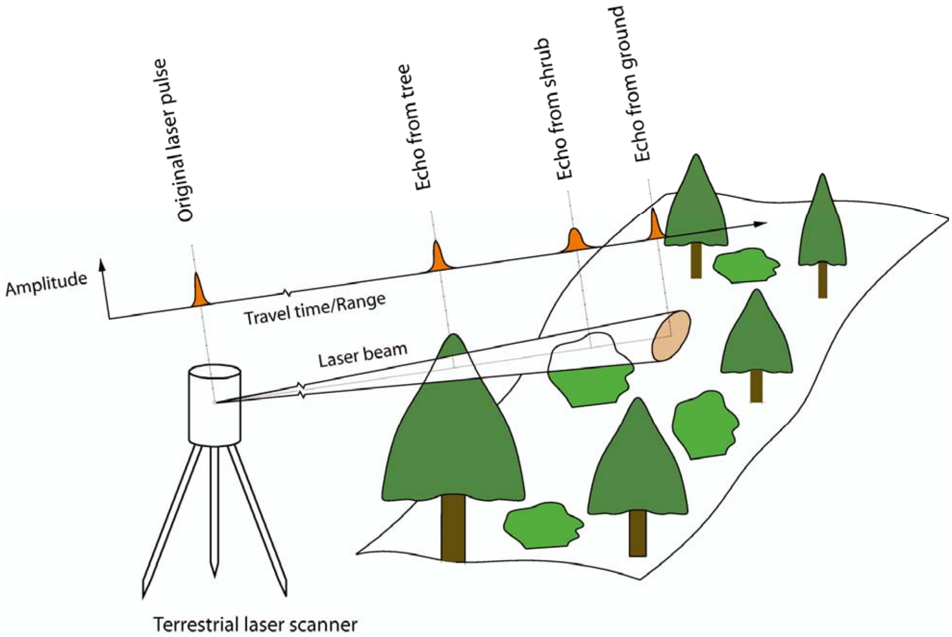


Fig. 3. The cartoon schematic diagram explains the problem and the usefulness of FWF TLS scanning in determination of the position of the ground surface (Roncat et al. 2010).

Presentation of results, dissemination

The dissemination of result has been started already parallel to the project start, initially in the form of poster and oral presentations, later on in the form of written contributions. We are about to publish further papers, the manuscripts are currently in preparation.

Measurement campaigns

Activities at measuring sites in Montafon

As it was mentioned above, sites in Montafon were considered mostly as Type B sites. In 2008 half of the measurement campaign was dedicated to two sites in the upper Ill valley in Partenen (Fig. 4). Unfortunately due to technical malfunction and measurement technological problems the acquired data are basically suitable for demonstration purposes only. Their quantitative use is hampered by the lower quality georeference. We also considered a site in Ganeu (also in the lower Ill valley), proposed by Bernhard MEIER (Stand Montafon), but the access to the site was found very difficult and to carry out yearly repeated measurements seemed to be difficult to realize, especially the emplacement and GPS measurement of retroreflectors.

Fig. 4. Location of the two scanner positions in Partenen. Note the traces of mass movements (rock slides, rock avalanches on the northern side of the valley (inset: preparation for measurement in Partenen-Loch). (Map: ÖK50)

In 2009 we made further attempts to scan other sites which were considered potentially as combinations of the two site types: tectonic movements as well as mass movements could be assumed in sites situated in the Suggadinbach valley, an almost hanging tributary valley of the river Ill.

Fig. 5. Measurement Site 1 (2009) Type A/B in Suggadinbach valley, near Untergampaping.

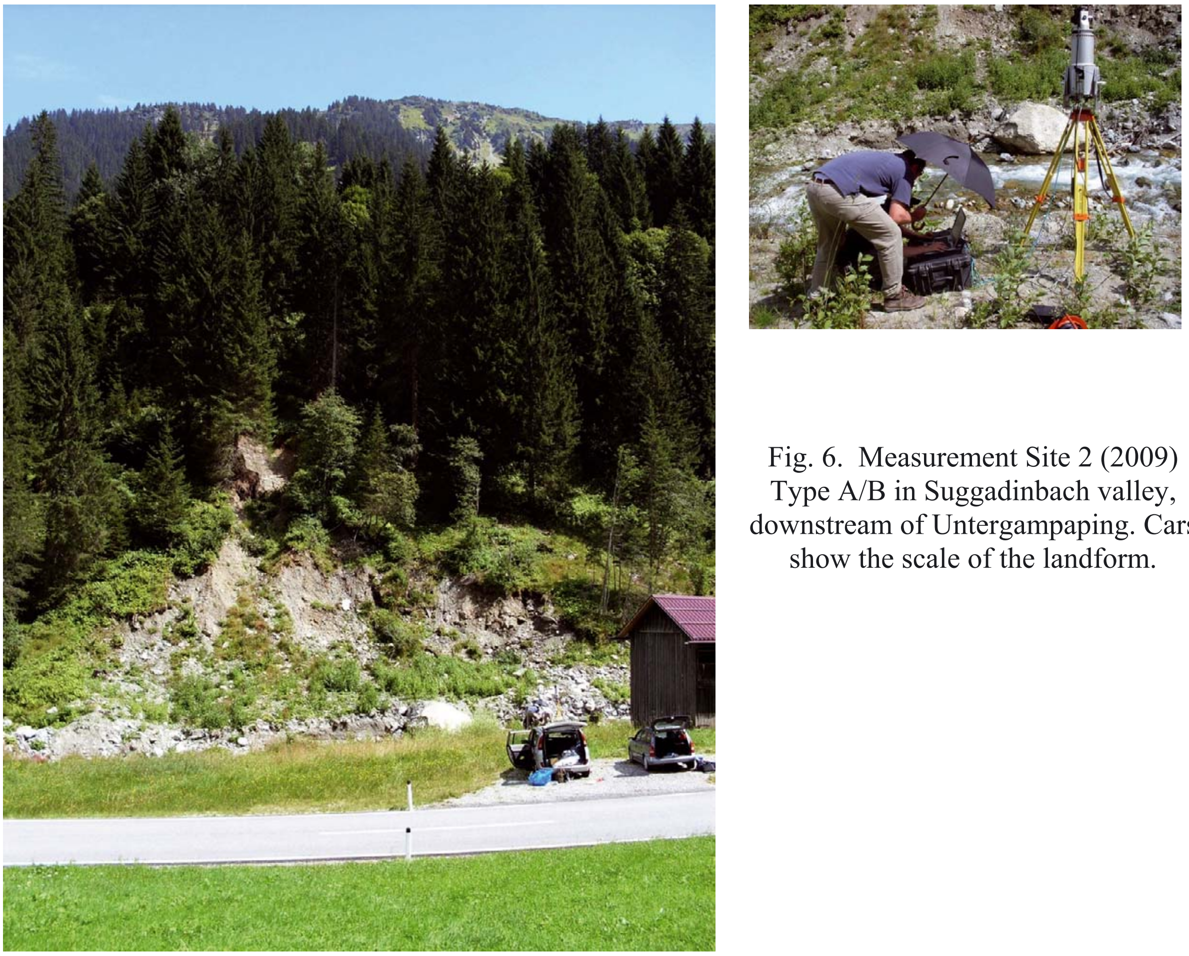


Fig. 6. Measurement Site 2 (2009) Type A/B in Suggadinbach valley, downstream of Untergampaping. Cars show the scale of the landform.

Fig. 7. Curved trees in the forest opposite to measurement site 2 in Suggadinbach valley, downstream of Untergampaping. Note the mushroom in the central panel showing the vertical direction. The shapes of the trees of all ages demonstrate the on-going slope processes.

Site 1 (near Untergampaping in Suggadinbach valley, Fig. 6) was selected because it is a very actively changing landform as it is shown by falling trees and the countermeasures (stone wall) built to decrease fluvial erosion. The material is highly unsorted; that fact could have helped to recognize which boulders moved or would be missing in the subsequent years.
Site 2 (Fig. 7) is situated more downstream in the valley. It is a similar, but less active feature, as it is demonstrated by the partial vegetation cover. In the opposite valley side covered mostly by coniferous forest. As it is visible in Fig. 7, the whole slope is involved in various types of slope processes (e.g. soil creep) continuously forcing the trees (of all ages) to cope with the deformation/motions.

Unfortunately, these measurements were not successful in the sense that the necessary absolute georeferencing accuracy could not be achieved. The main reason for that is the not enough isotropic displacement of the retroreflectors. In these cases the reflectors could be emplaced only at the opposite site of the valley, and only a few (if any) could be positioned really distributed in the scene. The consequence is that the positional accuracy is relatively high (i.e. bad). In many of the applications this accuracy would be acceptable, but in our case it is not, because we intend to detect short term change in the scene and these changes are in the same order of magnitude (or below) of the achieved accuracy. Consequently, in the final comparison the positional error and the observed change would not be separable.

As the distribution of the reflectors could not be improved (unless we include mountaineering techniques at very high costs), after having recognized this consequence, we have changed the focus of the activity.

Activities at measuring site Doren

Our measurements at the landslide-endangered site locality Doren (Bregenzerwald, Vorarlberg) started in 2008. The recurrent mass movement has been producing several events of various orders of magnitudes in the last decades (with major movements in the 1980s, in 2005, and in 2007; Fig. 8) endangering built-up property (Fig. 9). This area has been the target of numerous measurement campaigns during the decades, recently repeated Airborne Laser Scanning (ALS) measurements were carried out (initiated by the Landesvermessungsamt Vorarlberg), in order to monitor the motion of the material. The change of the landscape during the years is recognizable also visually at places.
The site is especially interesting for our purposes, since the area not only hosts the active landslide, but it is characterized also by the presence of plenty of microtopographic features that can be related to possible faults.

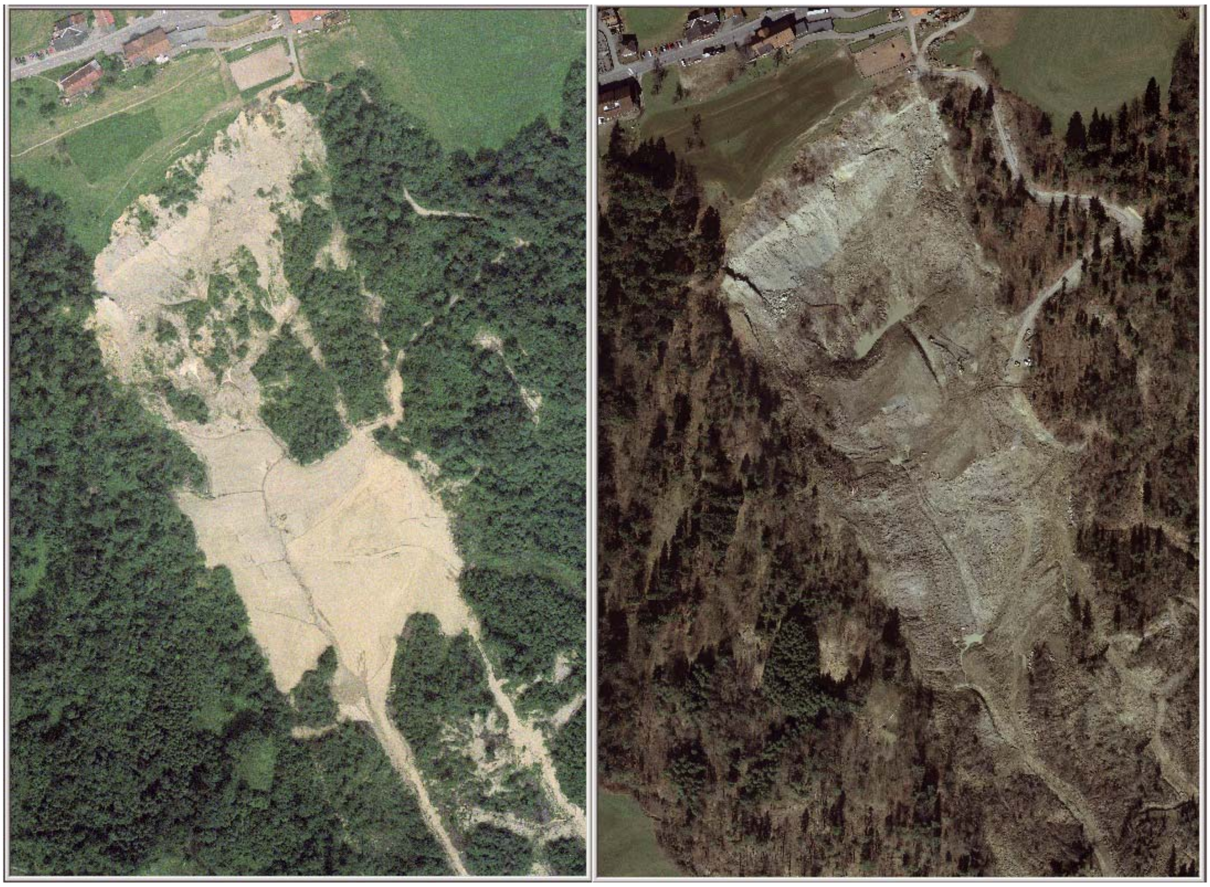


Fig. 8. Orthophotos of the Doren landslide in 2006 (left panel) and in early 2007 (right panel). Note the missing vegetation of the landslide surface in 2007, showing the severity of the landslide event in 2007. (Images are of courtesy of Landesvermessungsamt Vorarlberg.)

From 2008 on we have measured the area yearly; our measurement technology improved through the years in terms of applied scanning and co-registration techniques and mostly, coverage of the area including forested and otherwise vegetated areas (Table 1).

	2008	2009	2010	2011	2012
Measurement campaign	1-2 Sep	10-12 Aug	26-28 Sep	19-20 Sep	29-30 Aug
Instrument used	Riegl LPM-321*	Riegl LMS-Z420i	Riegl LMS-Z420i	Riegl LMS-Z420i	Riegl VZ-400*
Number of station positions	3	7	11	8	12

Table 1. Summary of the measurement campaigns 2008–2012. For the duration the days are indicated when measurements or observations happened in the Doren area. Asterisk (*) indicates the instruments with full-waveform properties.

In 2008 Riegl Laser Measurement Systems Co. (Austria) kindly provided a Riegl LPM-321 instrument; in the years 2009–2011 one of the TLS scanners of the institute (Riegl LMS-Z420i) was available for the measurements. Finally, in 2012 we used a Riegl VZ-400 instrument of the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archeology.

The number of station positions gradually increased yearly, except for 2011. Unfortunately, some of the great station points found in 2010 (that allowed a better coverage, especially on the toe of the landslide and both banks of Weißach) were destroyed by the increased erosional activity of the river due to its higher discharge; some other station points of 2010 have became inaccessible. In this year new station points had to be found.

Fig. 9. An overview of the Doren landslide seen from the Krumbach side in September 2011. Note the highly exhumed scarp of the landslide and the darker colours in the lower half of the scarp due to the evolved rills dissecting the scarp surface. View towards NW.

The timing of the measurements, August and September, are suboptimal, and basically a trade-off between the leaf-on vegetation state (disadvantageous) and lower risk of foggy and rainy weather (and the almost zero risk of snow cover)[1].

[1] This problem is known also from data acquisition over glaciers. The optimal time for flying is the end of the household year, thus maximum melt without new snow, but requiring good weather conditions. Interestingly, airplanes of surveying companies can be faster deployed once the flight plan is settled than groups of scientists can move from Vienna to Vorarlberg.

These circumstances (fog, rain, snow) may heavily influence or even hamper the measurements; on the other hand, the leaf-on state of the vegetation causes more problems as in the case of ALS: the incidence angle of the laser beam differs considerably from the ALS setting, because the laser beam hits the vegetation subhorizontally. In spring the measurements would be more advantageous, however the members of measurement team have many other duties in this time, and the schedule for instruments are also very busy in this season.

Fig. 10. The three instruments used during the measurement campaigns (see also Table 1): Riegl LPM-321, Riegl LMS-Z420i, and Riegl VZ-400 (from left to right). The first and the third instrument have full-waveform acquisition capability.

Fig. 11. An overview of the landslide scarp in 2011. Note the rills dissecting the hard surface of the scarp in the lower part. This lower area is already partly vegetated. Along some remarkable linear features this dissection advanced more creating a special wavy boundary of the not yet dissected surface.

We have had continuous problems with the emplacement of the retroreflectors that further decreased the possibilities of having a good georeferencing frame. Around the landslide scarp there were typically enough positions, however in the lower positions and in the Krumbach side it was always a challenge to find a position and especially to carry out the RTK GPS measurements to get the exact position of the reflector. In 2011 there were a number of points where the GPS measurements were not feasible.

Fig. 12. One of the station position (here in 2010) that was subsequently washed away (cf. Fig. 13) where the Weißach widened its narrow gorge. Note the area where people are standing did not exist anymore in September 2011. View towards ENE.

Fig. 13. The same area as in Fig. 12 in 2011: the small horizontal area visible in Fig. 12 is completely washed away. Note the trunks of the fallen trees and the enlarged small landslide in the Krumbach side (to the right). To compare the two images the coal-bearing layers of the Krumbach side provide some reference (also somewhat more exhumed). In the background the difference in ponding level can be compared, too. View towards ENE, for scale see people in Fig. 12.

Beside of the large-scale changes in the shape of the landslide, traces of other processes were also observed. The incision of the rills on the hard surface of the landslide has advanced dissecting large parts of the scarp (Fig. 11).

Data processing

According to our initial research concept the processing of the data was envisioned as conventional data processing of LiDAR technology. In this scheme the registered laser pulse data are converted from local polar coordinates (defined by direction data and the distance calculated from two-way travel time (TWT) of the laser pulse) to Cartesian coordinates and, as a second step, to point clouds georeferenced in national or global coordinates using the positional data of the scanner position registered by precise GPS measurements. The resulting point clouds (belonging to the same or differing scanner positions) can be then integrated to common point clouds.

The expedient accuracy required to detect the phenomenon, namely the displacement of the surface in multitemporal laser scanned data, has been found difficult to achieve. The various instruments used and geometrical settings of the points of the reference frames required improving techniques to georeferenced the data. The standard processing can only be used if the point density is good or at least satisfying. In the case of the vegetated areas the coverage is typically poor, in some areas, depending to uncooperative geometry very poor. In order to counteract this circumstance, we tried to establish as many station points as possible, but in many cases this was only partly successful.

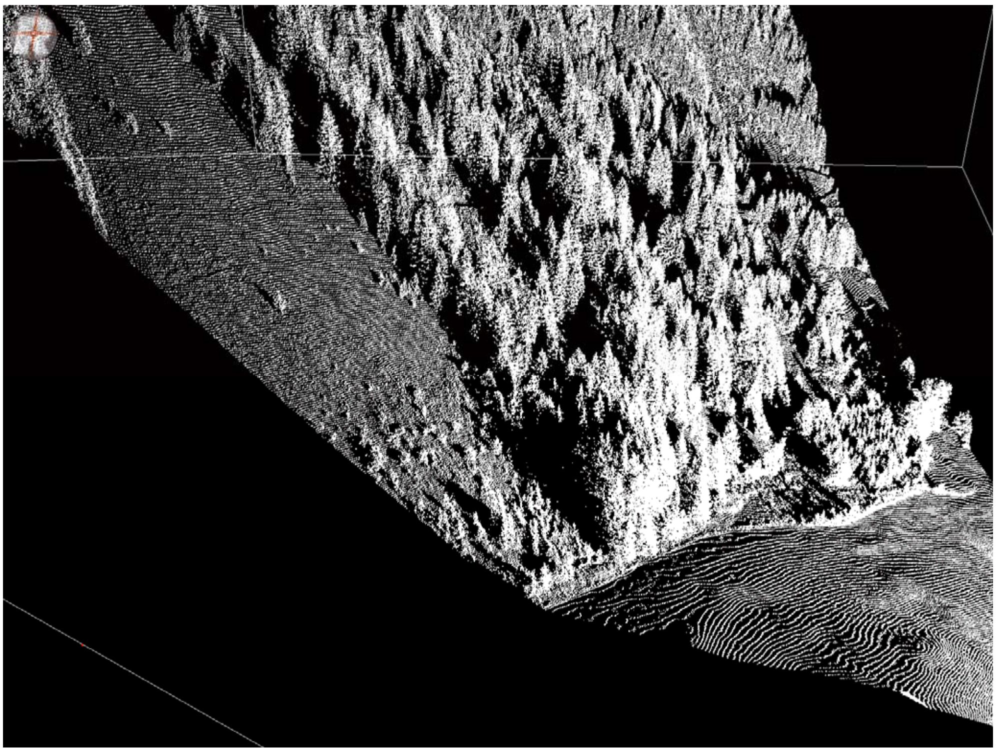


Fig. 14. A point cloud visualization in Partenen. Note the typical lack of ground points under the vegetation. (View is towards the NE. Cf. Fig. 4.)

Processing of the point clouds of the various campaigns

2008

In this year the processing was partly hampered by the hardware/software failure in one of the station points in Montafon, another one had been filtered out because of the poor accuracy resulting from the uncooperative geometry of the

measured reference frame. Furthermore, in the densely forested area there were unexpectedly too few ground points to establish a robust DTM surface in the vegetated areas (Fig. 14).
In Doren, however, the processing yielded an acceptable point cloud, even if, compared to the later years, the point density was too low at places. The station point in Krumbach was somewhat too far away, so we achieved a good overview of the visible area, but this point cloud could not contribute too much in terms of point density (see Appendix A, Fig. A1).

2009
The three scanned area are of various size and the retroreflector settings were quite different. The Suggadinbach valley measurement provided unsatisfying accuracies, but often high point densities.
The Doren results were very promising as it was possible to establish new station points in the Krumbach side. This improved the whole point cloud. Later a 9 cm vertical shift has been detected one of the data sets (around the toe of the landslide), after correcting for this shift the point cloud became dense and the result is a real improvement in comparison to the previous year data (Fig. 15, top left panel).
Owing to the more uniform point density the interpolation of the DTM was more successful, therefore the resulting surface is much more accurate to reveal the displacements in the landslide.

2010
Owing to the cooperative environmental circumstances (e.g., lower water level of the Weißach, river avulsion, relatively stable soil in the upper region of the Krumbach side), the extensive search for suitable station points and the refocussing the activity exclusively on Doren yielded the largest extent of point cloud scanned (Fig. 15, top right panel). The many station points and high percentages of overlaps within the point clouds of various scan positions needed a more elaborated processing in order to produce a high-quality output. During the processing it turned out that some areas of the rim was even visible from the station point beside the Weißach. Relatively large vegetated areas could have been also interpolated.

2011
The second half of the previous year was very wet in many places of Europe. A local consequence as an integrative effect of the varying discharge of the Weißach, was the increased incision. It rearranged the valley side of the landslide toe (a previous measurement station point washed away). Increased mass-wasting activity destroyed stable station points at the Krumbach side and caused partial falling of some trees that hampered visibility (Fig. 15, bottom left panel).

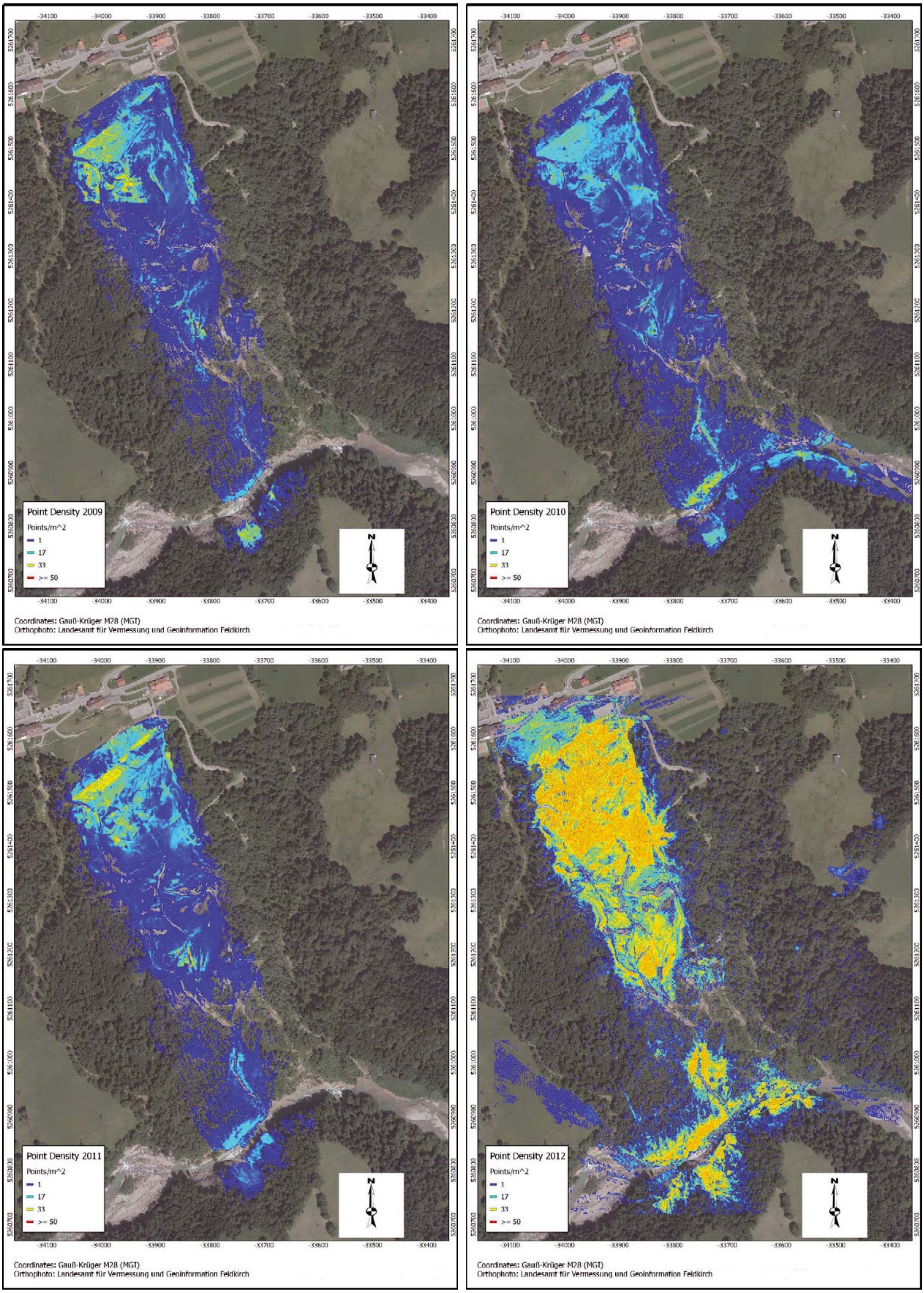


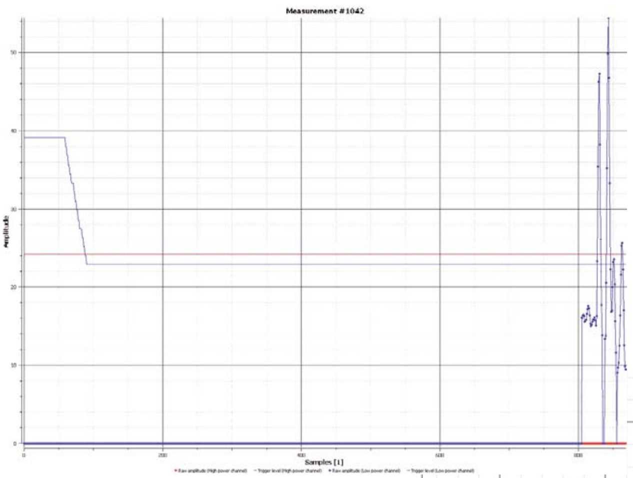
Fig. 15. Point density maps of years 2009, 2010, 2011 and 2012. Note the increasing point density and the varying point cloud coverage.

These circumstances resulted in georeferencing problems of some point clouds. Especially the processing of the point clouds of the Krumbach station points was found to be difficult. Some point clouds were too inaccurate (no enough retroreflector visible, similar to the Montafon case in 2008) so they could not be integrated into the final point cloud, and of course they were not used in the DTM calculation. As separate point cloud they are however can be used for visual evaluation to detect changes in the toe area.

2012
Learnt from the last years' experience, this year, beside of finding new station points, we focused on achieving higher point density. Assuming no geometrical obstacle in the way, the larger point density should be true for a large area, as far as the vegetation allowed (Fig. 15, bottom-right panel). Since this year we could use a faster terrestrial laser scanner (Riegl VZ-400) the scanning time of one station point did not play so important role as before.
The denser point cloud meant also a considerably better interpolation for those areas where the overlap of the station scans allowed that (mostly the yellowish and greenish areas in the bottom right panel of Fig. 15).

Processing the full-waveform data

According to the original concept, we intended to use mostly terrestrial full-waveform (FWF) scanners to overcome the problem of the vegetation.
In the first year we used a Riegl LPM-321 that was registering in this modus. Due to the aforementioned problems, however the expected accuracy and coverage could not be achieved.
Nevertheless, the FWF data showed great potential for the next years (Figs. 16 and 17)



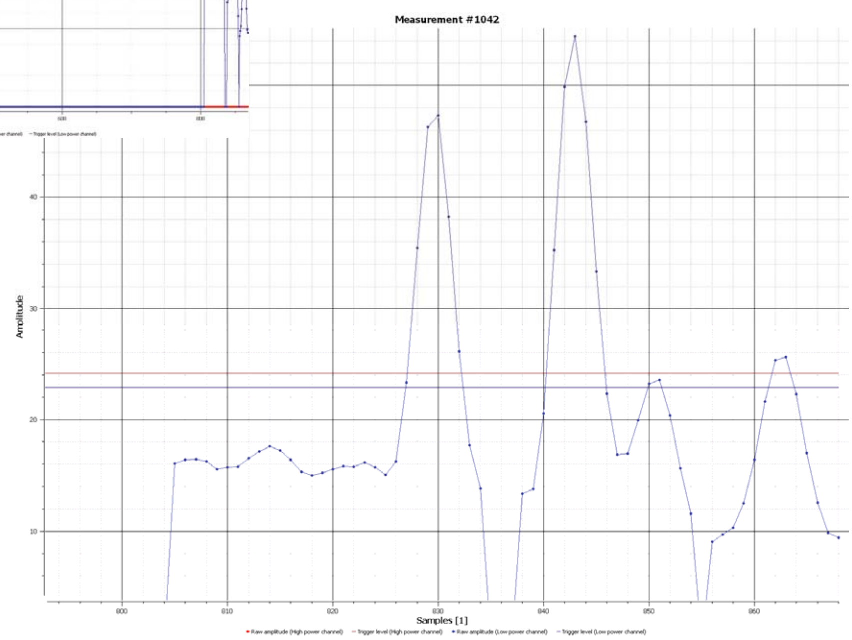


Fig. 16. A single full-waveform signal as registered by the instrument. The complete signal is depicted on the left panel; its last part is enlarged on the right. Note that more than 3 peak candidate exist in the signal that could be considered as valid targets. (The vertical axis is scaled in arbitrary units.)

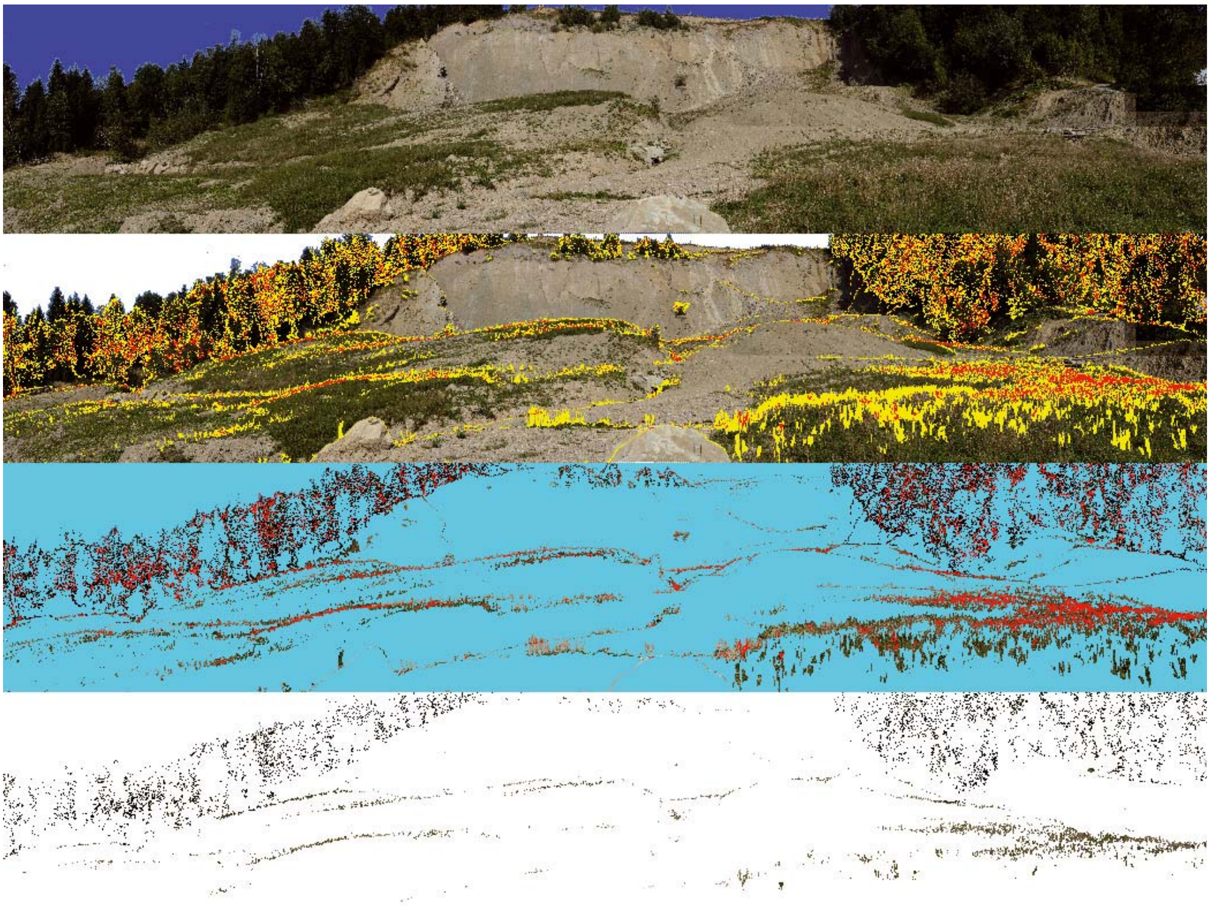


Fig. 17. Visualisation of the last three echoes of a scan in Doren (data of 2008 campaign). The image at the top shows a panorama image generated by the use of the 3D laser point cloud and the images of the digital camera mounted on the LPM-321 (blue colour indicates that the laser pulse corresponding to this direction had no echo). The pixels in the other images are in natural colours of they are the 1st (of maybe more than one) echo, or coloured according to the number of echoes (yellow: last of two echoes, red: 2nd or 3rd of three echoes).

The first year FWF data showed the main problems caused by the vegetation. In case of a forest the individual trees are standing more ore less parallel to each other, i.e. if we illuminate the setting with quasi horizontally propagating laser pulses then these pulses either get reflected by the tree canopy or, if they can pass through, echoes could be generated by tree trunks or the ground itself (cf. Fig. 3). The last case is not very frequent, but possible situation (Fig. 14).

Fig. 18. An overview of the Doren landslide in 2012. Buildings provide scale.)

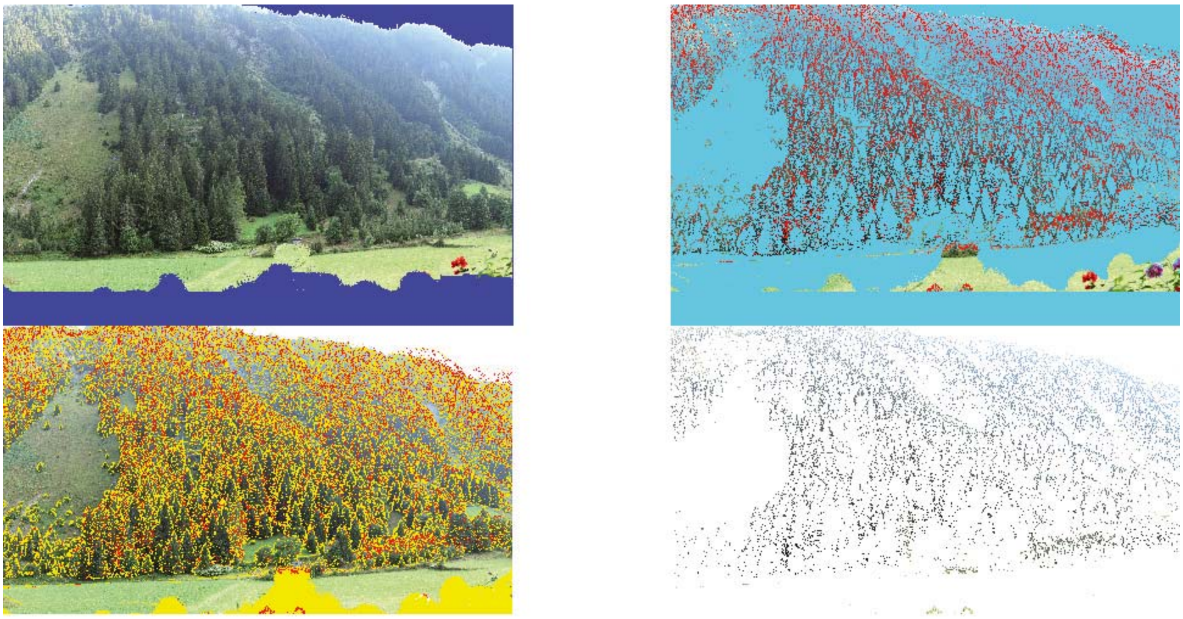


Fig. 19. Note the multitude of echoes in forested areas in this Partenen scan. (The top left image is a part of a panorama image that is used as background for the other three images. In the other three images the various echoes are visualized, for colours see Fig. 9.)

However, at a landslide, especially in the toe region, the tree trunks are not vertical anymore as the plants try to react to the displacement (Fig. 18), deformation adjusting their growth, furthermore the wash out and the other erosion processes often take the supporting material away, so that the trees became tilted, or get fallen. This complex structure of the vegetation generates many echoes, and reduces the probability to of the further penetration of laser pulse. Even if the pulse can penetrate, as the ground surface undulates strongly (Figs. 17 and 18), the angle of incidence on the ground, and therefore the footprint of the laser pulse varies also considerably (Figs. 17 and 19).

If we catch only a few of the echoes, they often represent partly other surfaces.

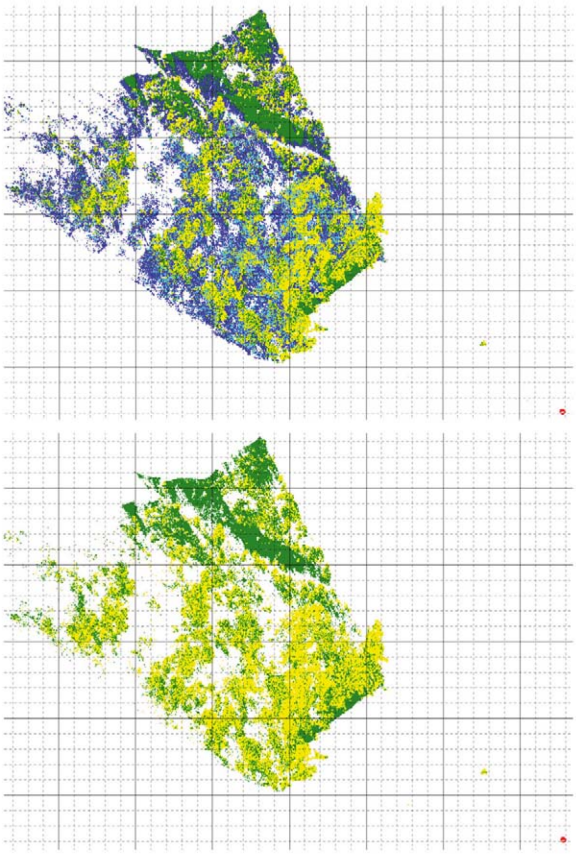


Fig. 20. A part of the point cloud of in the FWF data of 2012. In the top panel all echoes are visible (green: single echoes, yellow: first of multiple echoes, cyan intermediate echoes, blue last echoes). The scan position is marked with red. In the bottom panel only the single and first echoes are presented, this would be the result of the non-FWF scanning. Note the much denser point cloud and the better mapped objects.

Despite the long range of LPM-321 the solution of selectable three echoes did not seem to be an appropriate solution. As we had problems with the point density and the georeferencing, the issue of the FWF processing has been postponed.
It was recently, in the 2012 campaign when we could resume the issue of FWF data acquisition and processing, as we had the opportunity to use the much faster TLS device of Riegl VZ-400.
Although we still had the issue of the missing station points, the processed point cloud became much denser (Fig. 15, bottom right panel) and often improved even in the forested area (Fig. 20).
Since this data acquisition modus seems to be more successful, we plan to continue to use this technique in the future.

Results

The results are presented here only as brief summaries, for more details the interested Reader is kindly redirected to the relevant papers and abstracts. Furthermore, the results are presented in a logical order rather then in chronological order. This arrangement helps us to present the interdisciplinary character of our studies.

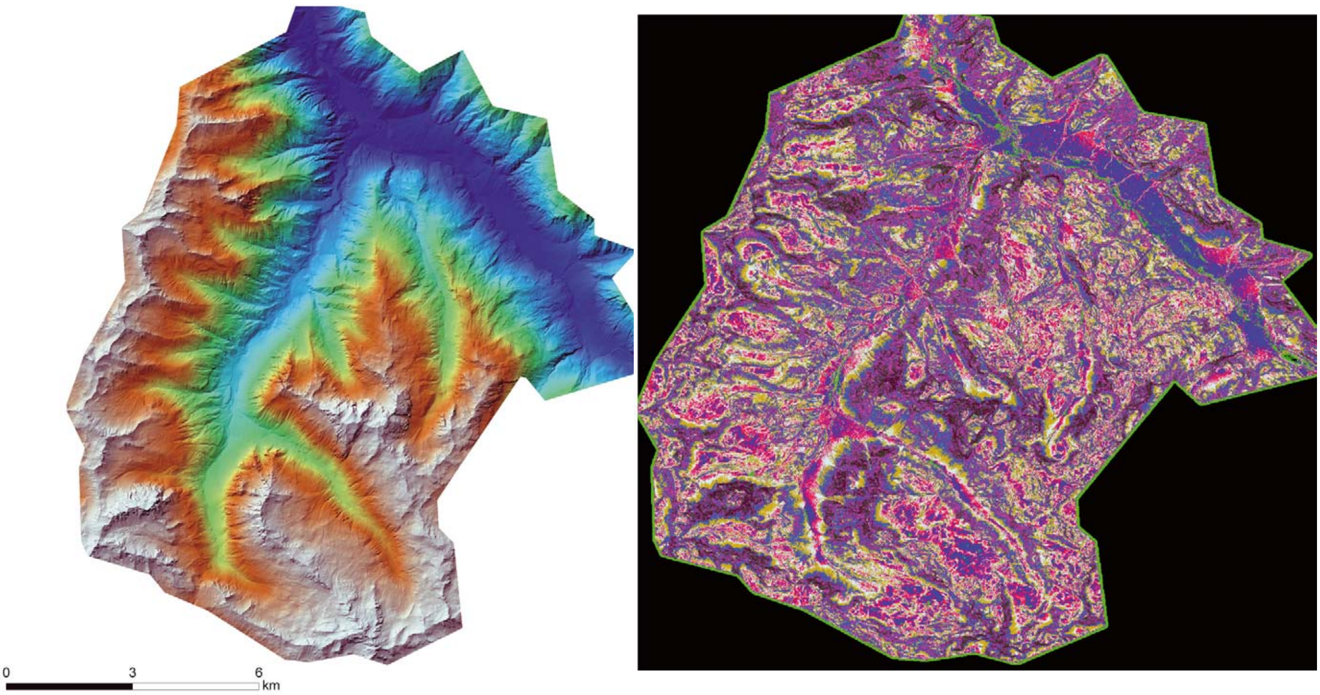
Results concerning the geological setting and environment: Montafon

As it was mentioned in the introductory part, we have had the opportunity to visit the Montafon area before the project had been started. In this context various in situ geological data have also been measured and geomorphological observations have been carried out. Additionally we had access to the ALS data (2003) of the region that could be used during the field work.
The Montafon area is strongly overprinted by the (post)glacial processes at various scales. The valley itself is a prominent glacial valley with oversteepened sides, on-going mass movements of various scales and being in inequilibrium, forming transitional landscape. The buttressing effect of the Pleistocene glaciers supported the steep walls eroded into the crystalline rocks which setting became unstable as the glaciers melted. The post-glacial geologic history of the Eastern Alps is dominated by erosion of these over-steepened valley slopes, increased fluvial erosion and gravitational mass-movements. Increased erosion enhances the morphology of and observability of structural features, especially in high-resolution LiDAR-DTM data. Montafon is located at the northern margin of the Penninic Units, between the NW-margin of the Silvretta nappe and the Northern Calcareous Alps (NCA) a NW-SE striking fault zone supports the formation of crystalline duplex structures. Additionally, the generally E-W striking NCA units bend towards SW reflecting the overthrusting of the Alpine nappes.

Fig. 21. Unsorted tillite is slumping and eroding in the Gargellen valley near Untergampaping (2009). Note the countermeasures: the wall is built-up of local boulders. (View is towards NE, persons provide scale.)

A further focus lies on the mountain slopes bounding the Gargellen valley that were subjected to surface and erosional processes related to glaciation. The Gargellen valley joins the Ill valley in the northern part of the study area. Both valleys hosted minor glaciers during the Pleistocene; the confluencing glaciers caused an increased stress on the bedrock. Thus, in this area effects of deglaciation are amplified. Typical processes acting on the slopes are: (i) frost shattering, (ii) gelifluction and after deglaciation (iii) surface runoff erosion due to increased precipitation, (iv) fluvial erosion by incising rivers. Since the beginning of the Holocene further mass wasting by sliding, slumping, fall, toppling and creep occurred. Assessment of the aforementioned micro- and mesoscale geomorphic features is needed to detect the ongoing processes and to determine the rates of deformation, incision and sediment production. The resulting tillites are often exposed by mass movements and erosional features (Fig. 21).

Fig. 22. Left panel: Shaded ALS DTM of Montafon; right panel: Unsupervised classification of the local slope histogram (ZÁMOLYI & SZÉKELY 2009b) indicates distinct lithological units. The mixture of black and purple categories (SW) are corresponding to gneisses. The talus cones in the NE-part of the image in the Ill-valley (blue pixels), depicted by red dots. Some structural features are enhanced, too.



The evaluation of the microtopography (ZÁMOLYI & SZÉKELY 2009b; Fig. 22) indicates that surface processes follow and reveal tectonic features. A remarkable difference in geomorphologic characteristics is observable between the NW-side of the Gargellen valley and the mountain slopes on the SE-side. Whereas in the NW areas cockpits are abundant in the higher elevated regions and glacial features (e.g. moraines) can be traced very accurately, the mountain slopes on the SE-side are steep, straight slopes with triangular facets and a drainage pattern that follows a systematic grid most probably provided by fault locations. This distribution of geomorphologic features is likely to indicate different exhumation rates and neotectonic activity.

Results concerning the geological setting and environment: Doren

Historical reconstruction. One of our important findings is that the Doren landslide has been active for many decades, even for at least two centuries. As we tried to trace back the evolution of the hillsides in Doren, archive aerial imagery (Fig. 23) have been studied (kindly provided by the Landes-vermessungsamt Vorarlberg) it became clear that the rim of the landslide can be observed relatively well in most of the images.

Fig. 23. Aerial photograph of the Doren landslide in the 1950-ies. Courtesy of Landesvermessungs-amt, Vorarlberg)

Furthermore, we found that interpreting the historical maps of the Habsburg Empire (Fig. 24), it is also possible to give a good guess about the position of rim even in terms of georeferenced images. Although these maps could be georeferenced with a relatively large error, locally, using the warping technique, it was possible to achieve a higher accuracy locally (Fig. 25; ZÁMOLYI et al., 2010).
The GIS integration of these maps and aerial images allowed the conclusion that the retreat of the landslide scarp accelerated in the last decades in the central and eastern parts of the rim. This can be considered to an alarming signal in the context of the built-up property, especially the livestock farming facilities in the eastern corner.

Fig. 24. Top panel: Georeferenced map of the Doren area in the Second Military survey of the Habsburg Empire. Lower panel: A shaded version of the ALS DTM of 2007 is draped over the same map (ZÁMOLYI et al. 2010). Note the relatively high accuracy.

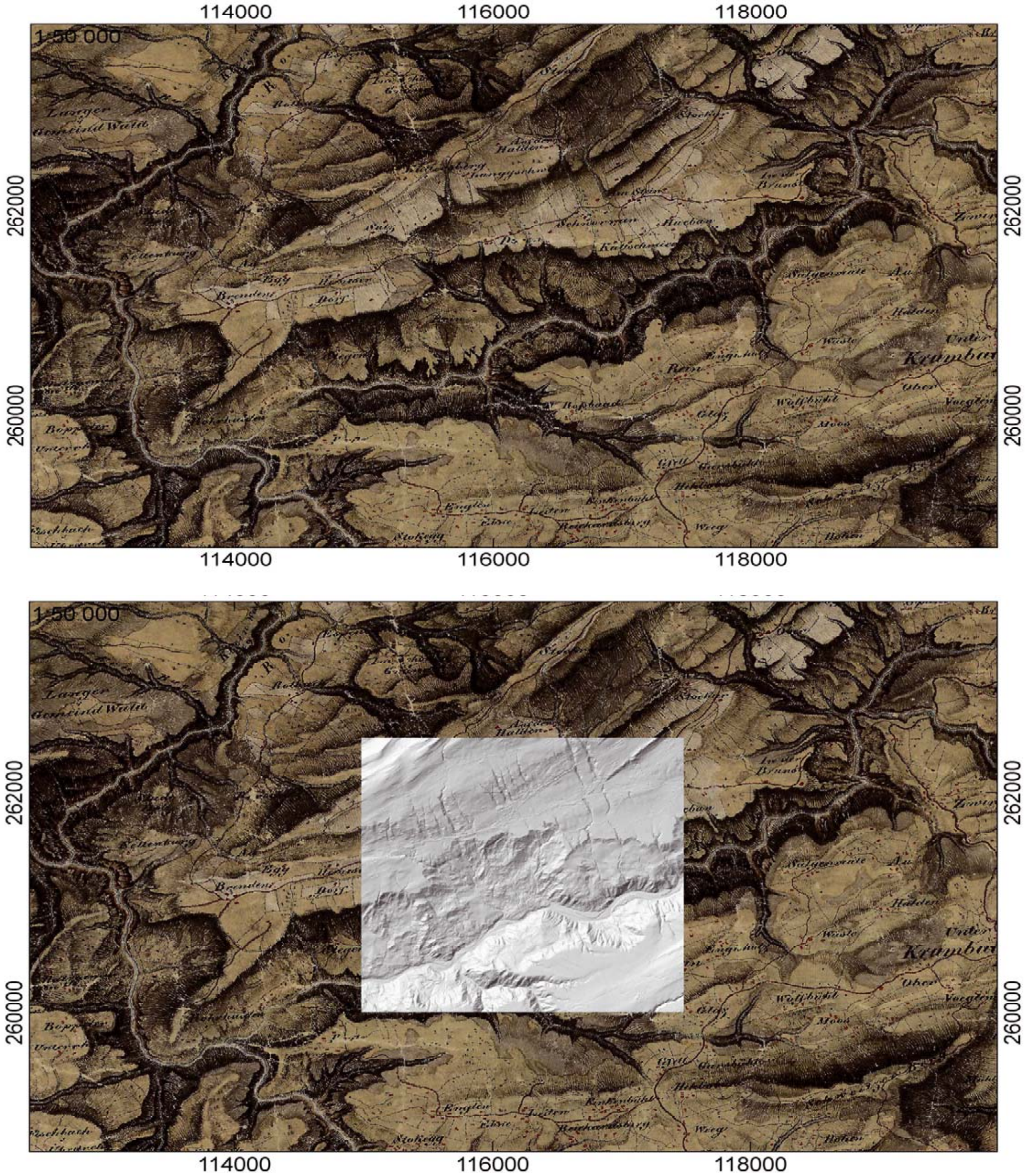
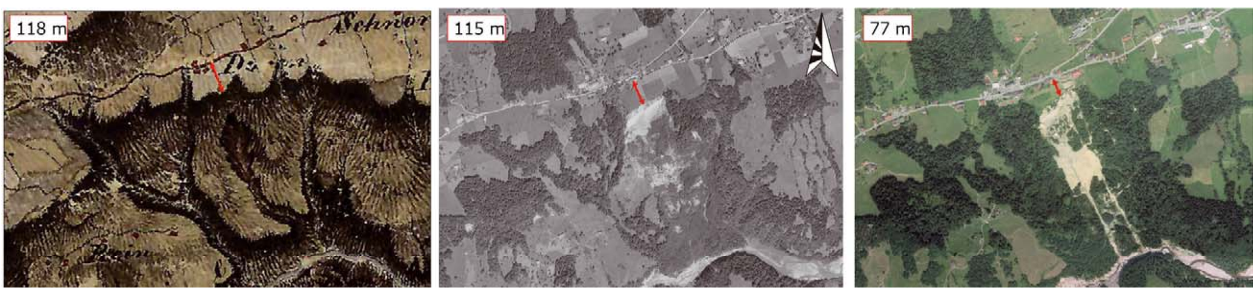


Fig. 25. The decrease of the distance of the landslide scarp rim to the road in the last centuries. Left: 2nd Military Survey (ca. 1850), middle panel: aerial photo (ca. 1950) , right panel: aerial photo (2006). Red line indicates the measured distance (ZÁMOLYI & SZÉKELY 2010).



Structural geological observations. If the lithological properties allow, erosional enhancement of the structural directions may develop (see e.g., Fig. 24, bottom panel). Often such geomorphic indicators are characterized by a micro-scale relief. In order to be able to make judgement about the geological context of the landslide, extensive structural geological observations have been carried out in the vicinity. Doren is situated in the Molasse Zone characterised by various clays, sandstones, and calcareous sandstones. The relief is is due to the combined effects of the relatively high erodibility of the rocks and the post-glacial surface evolution of the area. As the strata mostly consist of Kojen Formation, the material is originally of mixed kind, including some fine-grained matrix in some cases, often with strongly varying grain size composition, therefore the structural geological features (slickensides, joints, etc.) can be developed to various extent. In some cases the weak zones simply rearrange the intergranular space by compacting the material moving the grains relatively. On the other hand sometimes observable joints may develop. At some places of the landslide scarp surface slickenfibre was also observed, indicating slow development of faults.

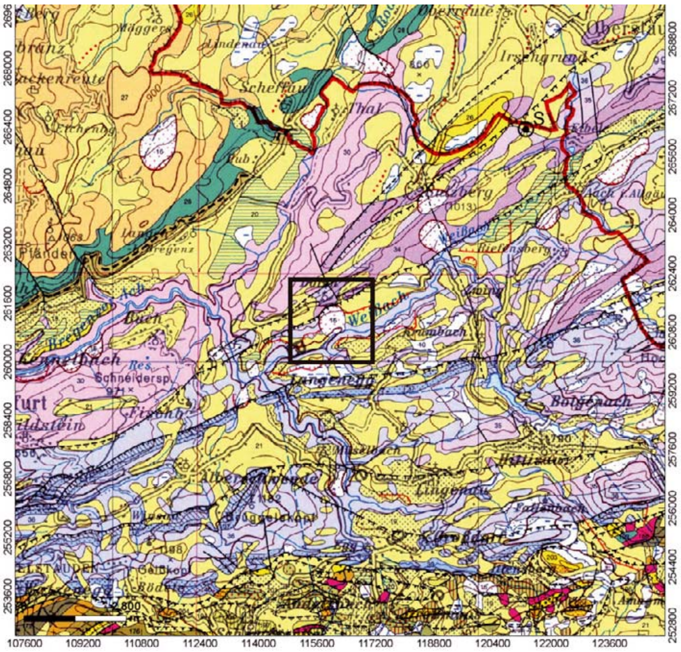


Fig. 26. Geological map of the area (OBERHAUSER 2007). Black frame highlights the Doren landslide.

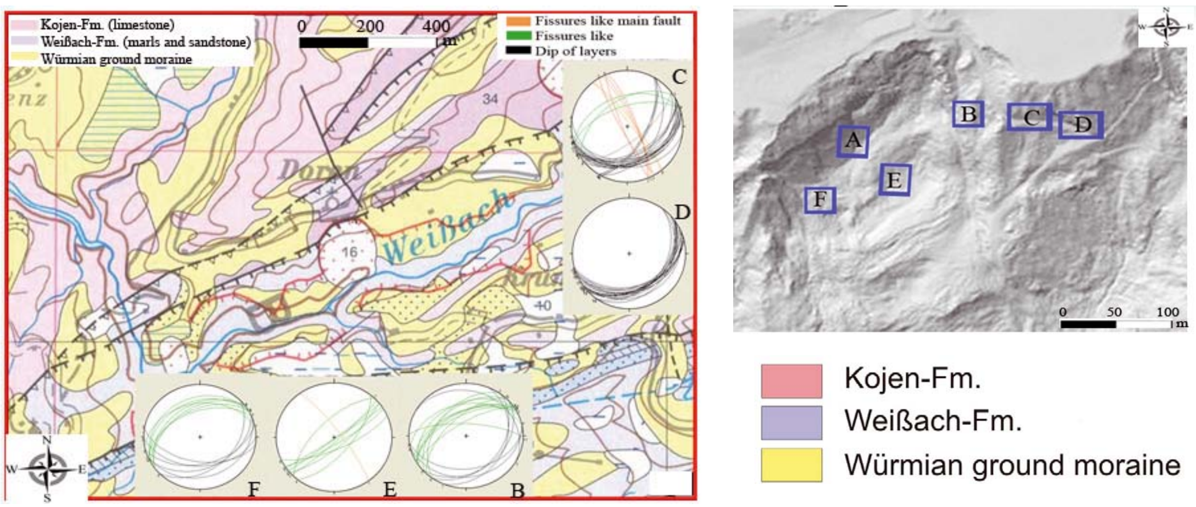


Fig. 27. Left panel: Geological observations in the vicinity of the landslide, right panel: location of the measurements and legend for the three major geological units of the area (Figure: POCSAI et al. 2011).

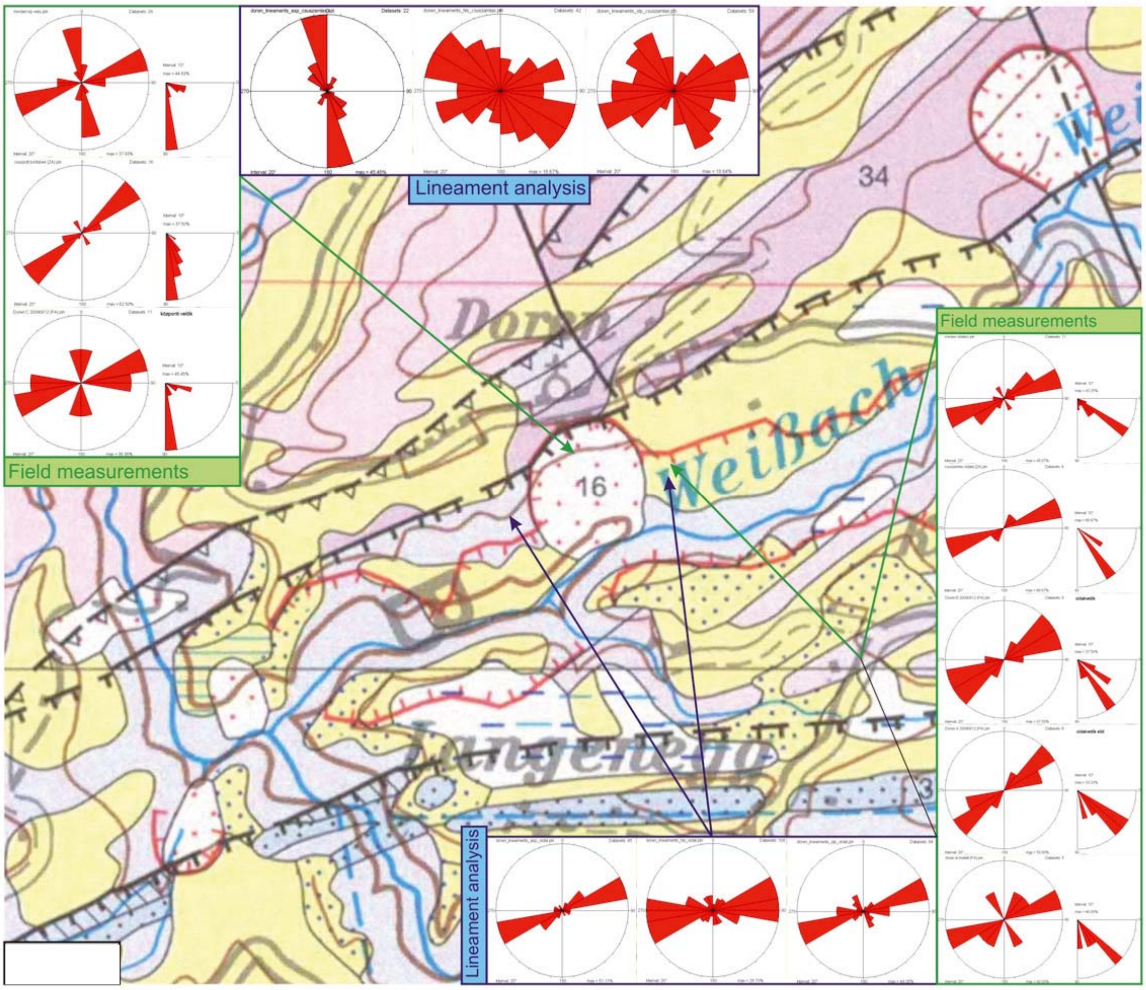


Fig. 28. Comparison of the azimuth distribution of lineaments analysis (blue-bordered inset) to that of geological measurements (green-bordered inset). For background and colours see Figs. 26-27. (ZÁMOLYI & SZÉKELY 2009b)

The LiDAR DTM has been processed to enhance microtopographic features, especially gullies and rills. These linear features were identified in the extended vicinity of the landslide and digitized in vector format. The resulting polylines were then analysed in various ways: rose diagram calculation and comparison with the general tectonic directions indicated in the 1:100000 scale geological map were carried out (Fig. 28).

In the light of the directional distribution of the digitized lineaments, we can state that the main directions are similar to that of the observed geological linear features.

The microtopographic features show correlation with the major tectonic direction (NE-SW) and with another direction NNW-SSE, indicated as subordinate. Interestingly there is a third, underrepresented orientation of WNW-ESE that is not indicated in the aforementioned geological map, these were observed mainly on the landslide scarp surface. It is noteworthy that the latter ones are aligned with the erosional rills of the scarp.

The place where these three directions seem to meet coincides largely with the area affected by the landslide. According to our working hypothesis (e.g., ZÁMOLYI & SZÉKELY 2009b) at the focal point of the three structural directions the enhanced erodibility of the rocks due to microfractures, and consequently the material of the moderately steep slope may start to creep or even to move if the previous meteorological and hydrologic conditions decrease the stability of the slope.

Results and considerations about geodetic setting and data acquisition

As more and more experience has been accumulated about the selection of station points and emplacement and positioning of the reference targets (retroreflectors) we expected to achieve better and better coverage and accuracy. However, the dynamic nature of the landslide counteracted and some previously well-designed and useful reference points were either destroyed or became inaccessible. In consequence, in many cases we faced poor visibility conditions of the retroreflectors; in case of one station point it was not possible to reconstruct the position because there were not enough reflectors visible. This is the reason why the measured area increased until 2010 and dropped in 2011. The large extent of the measured area that was achieved in 2010 was, unfortunately, not maintainable from 2011 on. However, for the main part of the landslide it was possible to create an appropriate DTM coverage. It has to be emphasized, however, that the resulting DTMs can be considered accurate only where the bare rock or sediment surface is visible, i.e. the coverages that can be considered as accurate have specific spatial distribution for each year, the accurate patches (of various sizes) varies from year to year. This property then influences the accuracy of the derivative products as well.

The TLS-data based DTM is, in some respect, comparable to those of generated from airborne LiDAR data captured in the previous years. However, it should be noted that further improvement and masking of non-measured areas are necessary. Furthermore, at some places, somewhat unexpectedly a proper georeference cannot be established for given vicinity. For these areas the local accuracy is expected to be better, but globally the individual points have much higher positional error (e.g. vegetated areas) valley sides of the U-shaped valley are typically visible from farther distances. The main problem for geodetic measurements that caused a lot of problems and decreased the achievable accuracy is that all the possible retroreflectors that can be emplaced in the scene are confined into a relatively thin 3D region, close to a plane aligned with the valley side. Therefore, it is an almost ill-posed setting for the mathematical solution. Laterally, along the valley side, the position of the points can be calculated quite accurately, however, the perpendicular to the confinement “plane” (thin volume) this accuracy is typically not achievable.

In summary we can conclude that the changing visibility and the varying scatter of reference points will define an accuracy surface over the scene that can be only improved if the point density is increased so that elements of the point cloud are derived from more than one station point. Obviously, if these station points are close to each other, this will not improve considerably the accuracy of the resulting point cloud.

We have further developed methods for the classification of the point clouds. The primary aim is to find the ground, but detection of vegetation is necessary to i) eliminate it, and ii) understand parameters of the vegetation, as it is also related to geomorphic processes, and iii) to estimate the quality of the terrain model. For buildings, also visible in the Appendix C (Fig. C1), the situation is different.

The classification procedure applied here is the same as in the case of the classic airborne laser scanning (ALS), however, the behaviour of the point cloud is in many respects different. This is due to the acquisition geometry. In the case of ALS the laser pulse is emitted towards the ground surface confined around the nadir direction within a relatively small conical angle, so that the objects are illuminated more or less from above. This allows the laser pulse to penetrate among plants (subparallel to their growth direction) resulting in numerous echoes from the ground surface. However, in the case of terrestrial laser scanning, the growth of the vegetation is rather close to perpendicular to the laser pulse path, therefore, as we have already seen above, the illumination of the vegetation has a considerable self-shadowing effect. Fig. 29 demonstrates this effect displaying a steep alpine slope with varying coniferous tree cover.

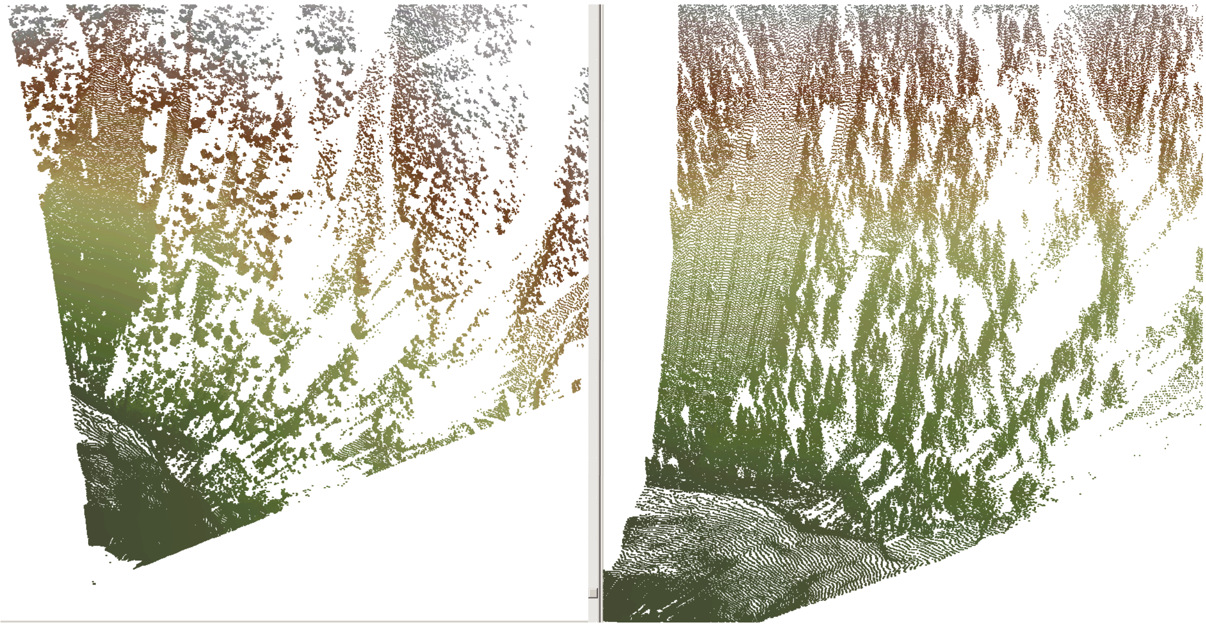


Fig. 29. Visualization of the self-shadowing effect of the vegetation. A part of TLS scanning data set (Partenen, Vorarlberg) highlights the problem of the quasi-perpendicular growth of the vegetation to the scanning direction. The left panel is a map view, the right panel is a 3D rendering (for a better visualization the background is white). The scanner position is in the bottom left corner. Note the shadowing effect of the coniferous trees away from the scanner. The varying vegetation density demonstrates the varying penetration depth: in case of loose stands the ground is still visible (in the left part). In the far left there is a grassland for comparison.

The self-shadowing effect is suppressed to a certain extent if the point clouds acquired from various scanning positions are merged. If the coverage of the area allows there can be quite acceptable regions with respect to the point density. The 2008 data acquisition is a good example for that (Appendix A, Fig. A1). A classification example is shown in Appendix C (Fig. C1): for almost the whole area of the landslide scarp is at least partly visible, therefore the classification was successful separating the ground points from the low and mid vegetation. The few red-coloured points (classified as “below terrain”) are the result of the robust hierarchical filtering intended to determine a relatively smooth terrain. The points that are found to be situated below this generalized surface can belong to either points of small erosional rills or pits incising below the general (trend) surface, or, in case of a more rugged or undulating terrain, when the robust filtering somewhat overestimates the position of the actual surface, they can represent a part of the trend surface.

Change detection and tracking the deformation

From geoscientific point of view or concerning the research on natural hazards in the case of landslides and similar phenomena the focus is basically on the change of the surface: that may reveal the processes and rules that determine the future state of the phenomenon. In other worlds the changes, their spatial pattern and temporal rates are the most interesting data that we intend to derive.

The change itself can be observed only if we apply special instruments that are sensitive to deformation or displacement. In case of laser scanning or other photogrammetric methods we sample the reality both in time and space. The success of the change detection is primarily based on the successful (i.e. good enough) sampling, and secondarily whether we can read out the change from the gathered data.

For detecting the change an optimal sampling strategy should be applied. To design that it is inevitable to estimate the speed, the rate of changes, otherwise we cannot detect the change or we spend too much effort for the data acquisition.

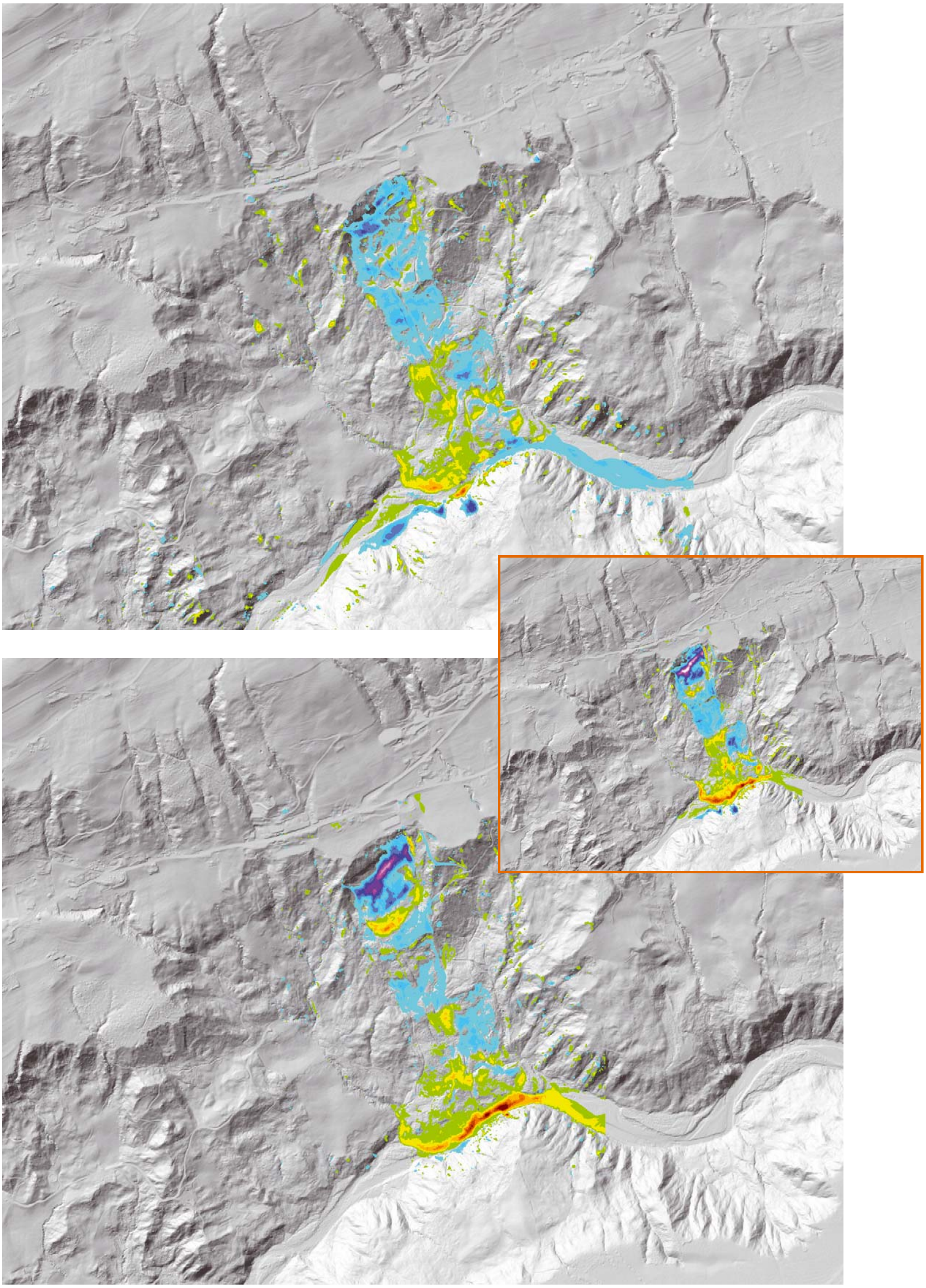
Unfortunately phenomena like landslides tend to have changes on various temporal and spatial scales. For certain time periods it seems that nothing happens, then later a sudden event can happen. The spatial distribution can also be very heterogeneous.

In case of the Doren landslide, after the 2007 big event, the Landesvermessungsamt Vorarlberg, together with the Wildbach- und Lawinenverbauung (Gebietsbauleitung Bregenz) installed and managed continuous measurement system at the Doren landslide. Since the landslide was considered settled for a while, after few years the continuous measurements have been stopped and regular measurement regime has been introduced. These pointwise methods, however can only reveal motions to a limited extent, basically it is a measure of activity, but one can learn restricted information about the dynamics of landslide.

Our method, the terrestrial laser scanning has a much better spatial coverage and resolution, however, cannot compete in temporal resolution. Therefore the derived data should also be evaluated in terms of rates (even as sort of forecasts) in order to estimate changes.

The first idea, coming from the mathematical geometry, is the comparison of two surfaces: surface(t_2) and surface(t_1) whereas t_1 and t_2 are two moments in time so that $t_2 > t_1$. Such an approach is presented in the following figures (Fig. 30).

Fig. 30. (next page). Differential models calculated from ALS data (Landesvermess. Vbg.)
Top panel: $DTM_{ALS,2006} - DTM_{ALS,2003}$ The small framed inset: $DTM_{ALS,2007} - DTM_{ALS,2003}$
Bottom panel: $DTM_{ALS,2007} - DTM_{ALS,2006}$ (SZÉKELY et al. 2009)
Blueish colours mean surface subsidence, reddish/purple colours mean surface uplift.



This approach seems to be successful since it shows the most important changes in the area. On the other hand these data were suitable for such an operation because both datasets were ALS grids, the original point density was very similar and there is no problem with the calculation.
However, the next example (Fig. 31) shows already some problems with this approach.

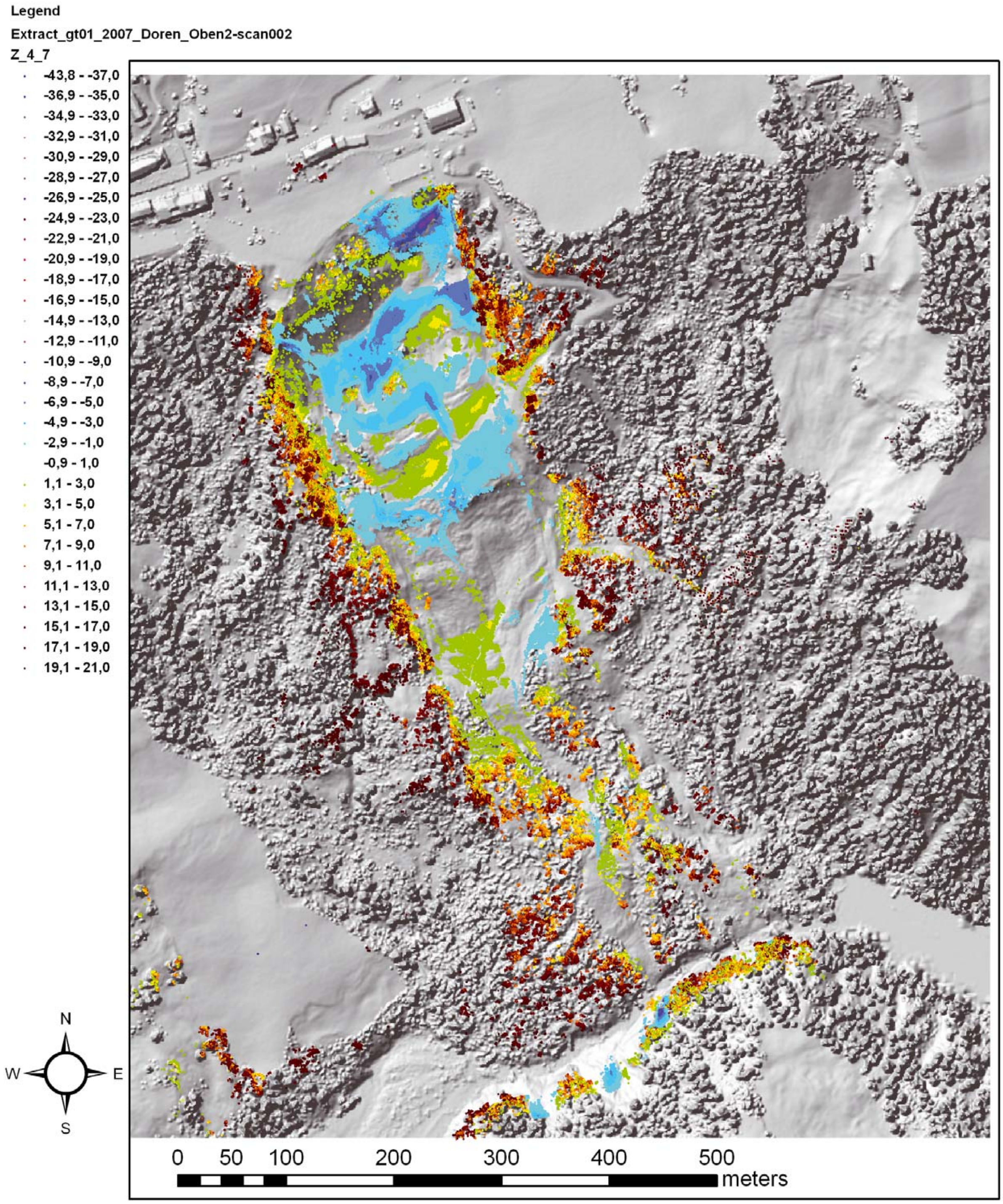
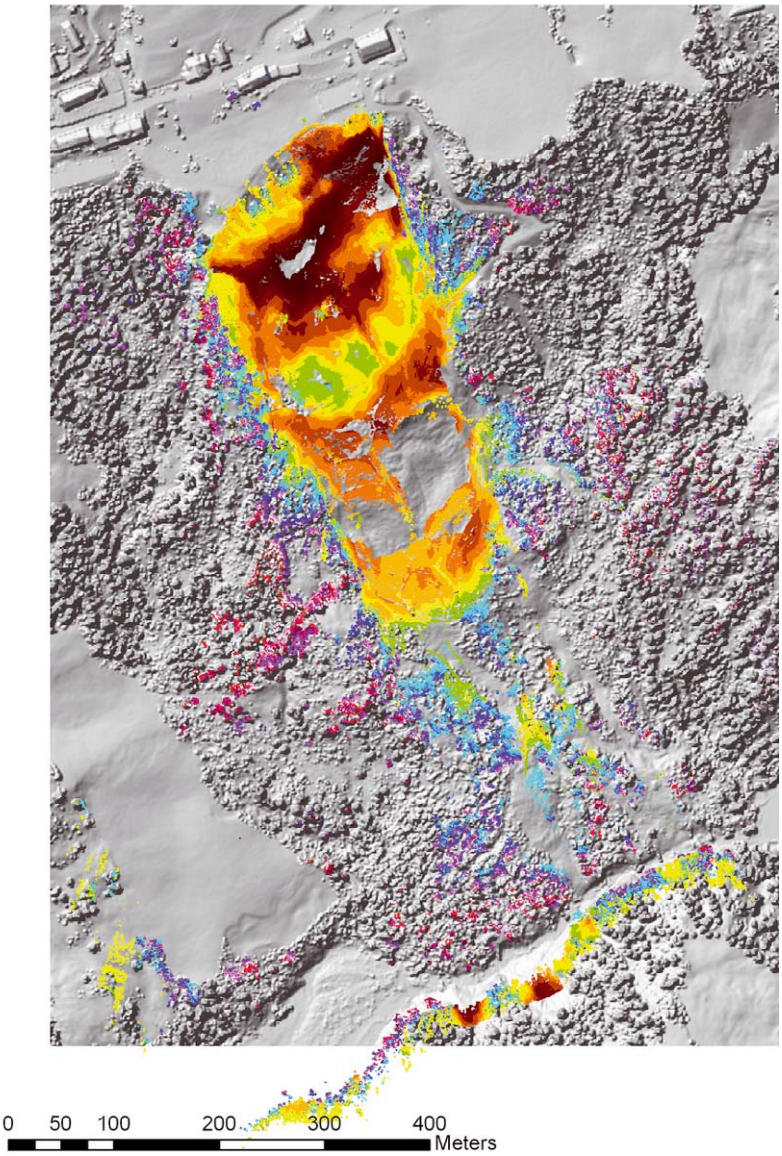


Fig. 31. A terrain change map of the Doren landslide area based on our measurements calculated as $DSM_{TLS,2008}$–$DTM_{ALS,2007.}$ Compare the pattern to that of Fig. 30 (SZÉKELY et al. 2009). See the text for further details.

If we have a look on the scale, it becomes obvious that most probably there is no place in the scene that changed more 30 meters in one direction or more then 20 meters in the other within one year. It is clear that there is a problem with the calculation of the TLS surface: at places it is not representing the ground but some other surface, the top of the canopy or some other intermediate (maybe not existing) surface.



On the other hand, the change is also visible, it is more or less in accordance with the changes of the preceding year, but this change of the landslide is mixed with erosion, mismatch of other surfaces, vegetation etc. And it is also obvious that there are places where there is practically no change and there are large areas where we do not really know, because there is no coverage in the 2008 data.

If we now have a look on the difference image of the TLS2008 and ALS2003 surfaces the picture is much more realistic, because the actual difference is much larger in the whole scene in five years (and two major events happened during this period of time).The dynamic of the motion is also more intelligible.

Fig. 32. A terrain change map of the Doren landslide area based on our measurements calculated as $DSM_{TLS,2008}$–$DTM_{ALS,2003}$. Compare the pattern to that of Figs. 30 and 31 (SZÉKELY et al. 2009).

The problem is now how to assess these type of changes if we know that there will be artefacts present in the one of the models or both, and there is displacement and deformation (see e.g., the toe area of Fig. 30).

We developed two analysis methods to detect such type of changes. Both are intended to somewhat robust, but, of course both have limitations. In the next sections these methods are presented.

<u>Modelling with planar facets.</u> The first method is based on the observation that processes often create long-lived or ephemeral quasi-planar features, due to the lithologic contrast, material motion, smoothing of external forces, etc. These small landforms then can survive so that they e.g. "travel" on the landslide and keep more or less their internal forms. If they keep their internal form then it would be possible to approximate them by a number of planar segments and then we could follow what happens to these element surfaces.
Of course the fitting of planes must be robust enough to tolerate noise, non-planar neighbourhood, it should be able to bridge small distances (e.g., rills, barrancos, etc.) The solution to this problem is coming from the 3D city modelling where one intends to convert the complex point cloud to assign the points to certain planar elements so that the planar element is not too far from the points.
The method has been presented in Dorninger et al. (2011). Here we just show some results. The interested author can find the methodical details in that contribution.

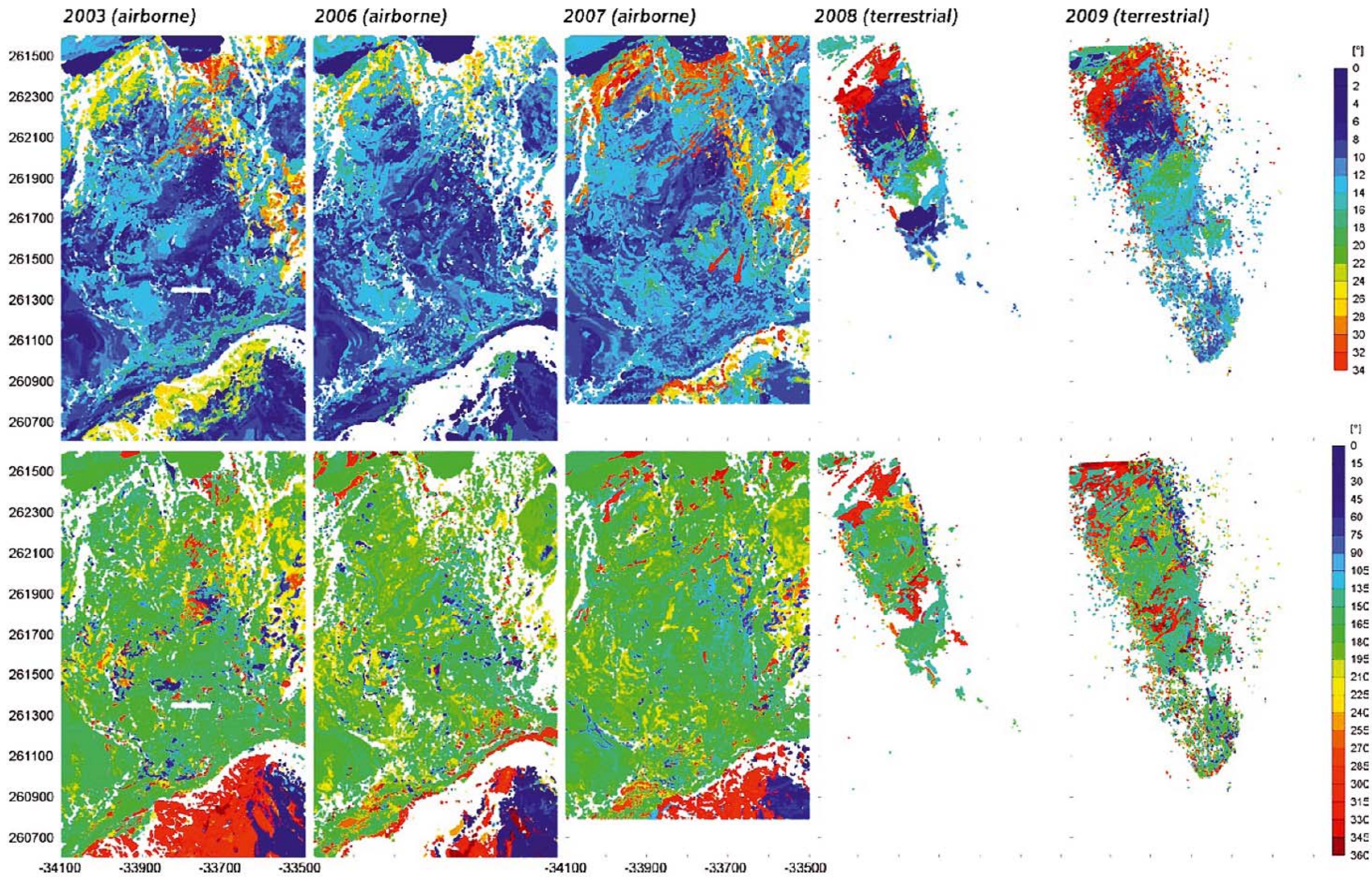


Fig. 33. Time series of the Doren landslide region from 2003 to 2009 (DORNINGER et al. 2011). The upper image series shows the slope angles of the fitted planes, the lower one shows their aspect angles. On both types of maps changes in the shape of the landslide can be observed. On the slope map, the progressive exhumation of the main sliding plane is clearly indicated by the on-going steepening along the main scarp, whereas on the aspect map of the ALS data, the change in shape of the landslide toe can be documented.

Fig. 33 shows a number of interesting features and properties of the method. The striking difference between the ALS and TLS data is due to the fact that the resolution of the ALS DTMs was set to 1 m, whereas in the TLS the point cloud was used to calculate the planar elements. This means that in the TLS the definition of an element can follow better the actual points what implies that in many cases a smaller patch will be found that can stand steeper. If the resolution is lower, like in the case of ALS, this will be averaged out.
In the ALS series the evolution of the toe is very well visible as the material protrudes downwards confining the stream to be narrower and narrower. In these figures it is not visible, but it was already mentioned above that this narrowed gorge had been opened in 2010 washing away a great amount of material.
One can ask why not simply take the slope and aspect of a generated surface? Intuitively this would produce more or less the same pattern.
Unfortunately this is not true in many cases. The reason for that the terrain is typically rougher than the one consisting of fitted planes, because (a) there are many rills, erosional features (b) there are artefacts in the fitted model (mostly due to remaining echoes coming from the vegetation).

Monitoring using 3D range flow algorithm. The other idea to track the changes is to consider the DTMs as frames of a motion picture and evaluate them accordingly.
In the computer vision industry there are methods to track certain object in a motion picture, or separate moving and stable objects, etc. To evaluate the changes, we have determined the 3D motion using the range flow algorithm, an established method in computer vision, but not yet used for studying landslides. The generated digital terrain models are the input for motion estimation; the range flow algorithm has been combined with the coarse-to-fine resolution concept and robust adjustment to be able to determine the various motions over the landslide. The algorithm yields fully automatic dense 3D motion vectors for the whole time series of the available data. We present reliability measures for determining the accuracy of the estimated motion vectors, based on the standard deviation of components.
As it was discussed above, parts of the landslide show displacements up to 10 m, whereas some parts do not change for several years. That is what mapped by the algorithm: the differential motion pattern is analysed. The results can also be compared to pointwise reference data acquired by independent geodetic measurements; we plan to carry out this comparison and a paper will be written about the method.
Here we show some preliminary results in the form of figures.
In interpreting the following we assume that the surface can be described as

$$Z = \mathrm{f}(X, Y, t) \qquad (1)$$

so that X and Y are horizontal coordinates and t is the time. Then the total change in elevation

$$\frac{dZ}{dt} = \frac{\partial Z}{\partial X}\frac{dX}{dt} + \frac{\partial Z}{\partial Y}\frac{dY}{dt} + \frac{\partial Z}{\partial t} \qquad (2)$$

so that

$$W = Z_X\, U + Z_Y\, V + Z_t \qquad (3)$$

In other words (U, V, W) is the velocity vector, W is the vertical component, U is the E-W and V is the N-S directed component.

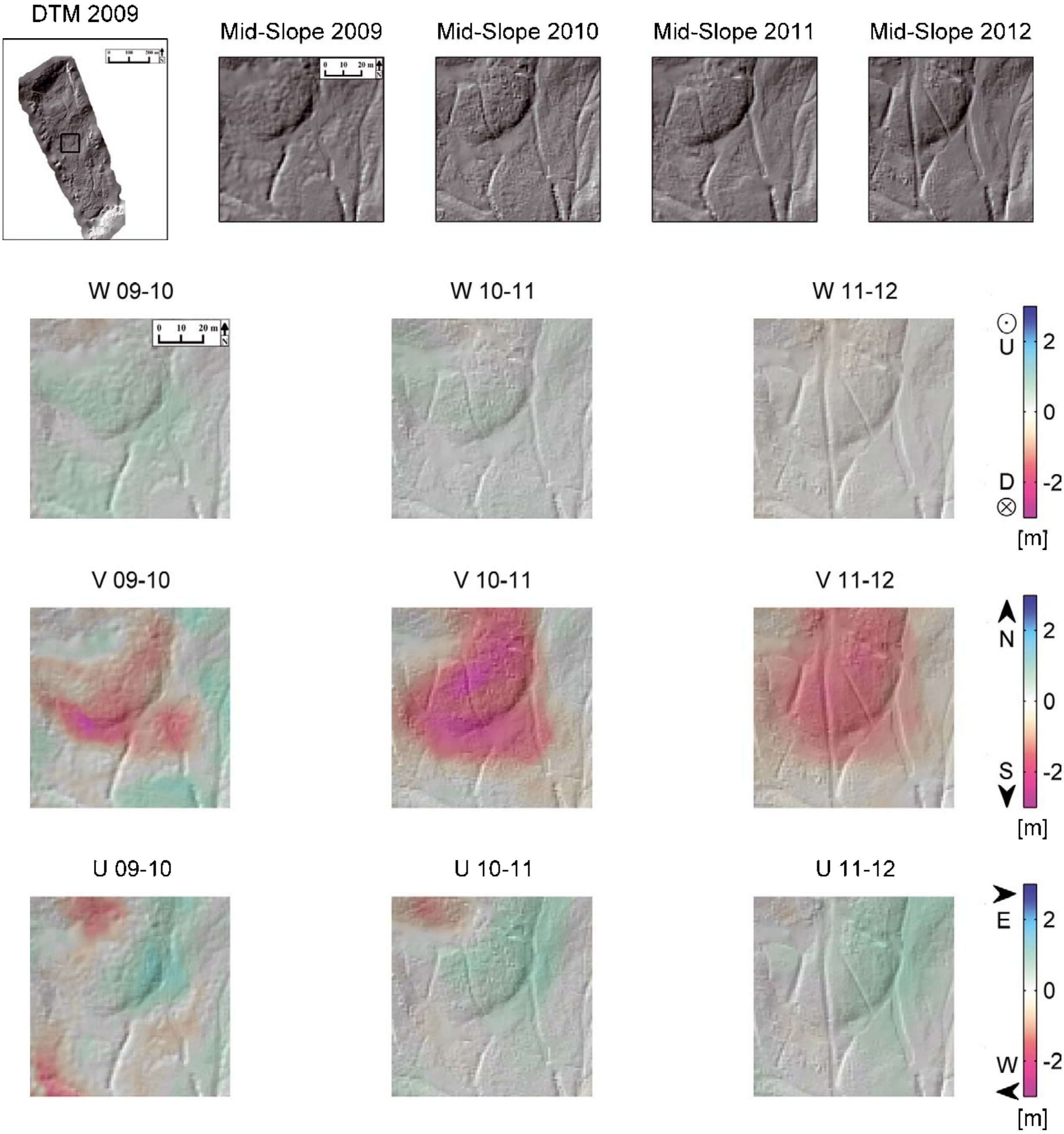


Fig. 34. Calculated velocity vectors of a selected small region (for position see the frame at the top left corner). The calculated TLS DTMs are in the top row (2009-2012). The next 9 maps show the velocity components of the three consecutive years. Units are in m/year (GHUFFAR et al. 2012 and in prep). W vertical velocity (positive downwards) V (N-S velocity, positive to N) U (E-W velocity, positive towards E). This internal small mass movement shows an interesting, yearly increasing southward moving with some spreading to east. The vertical component decreased.

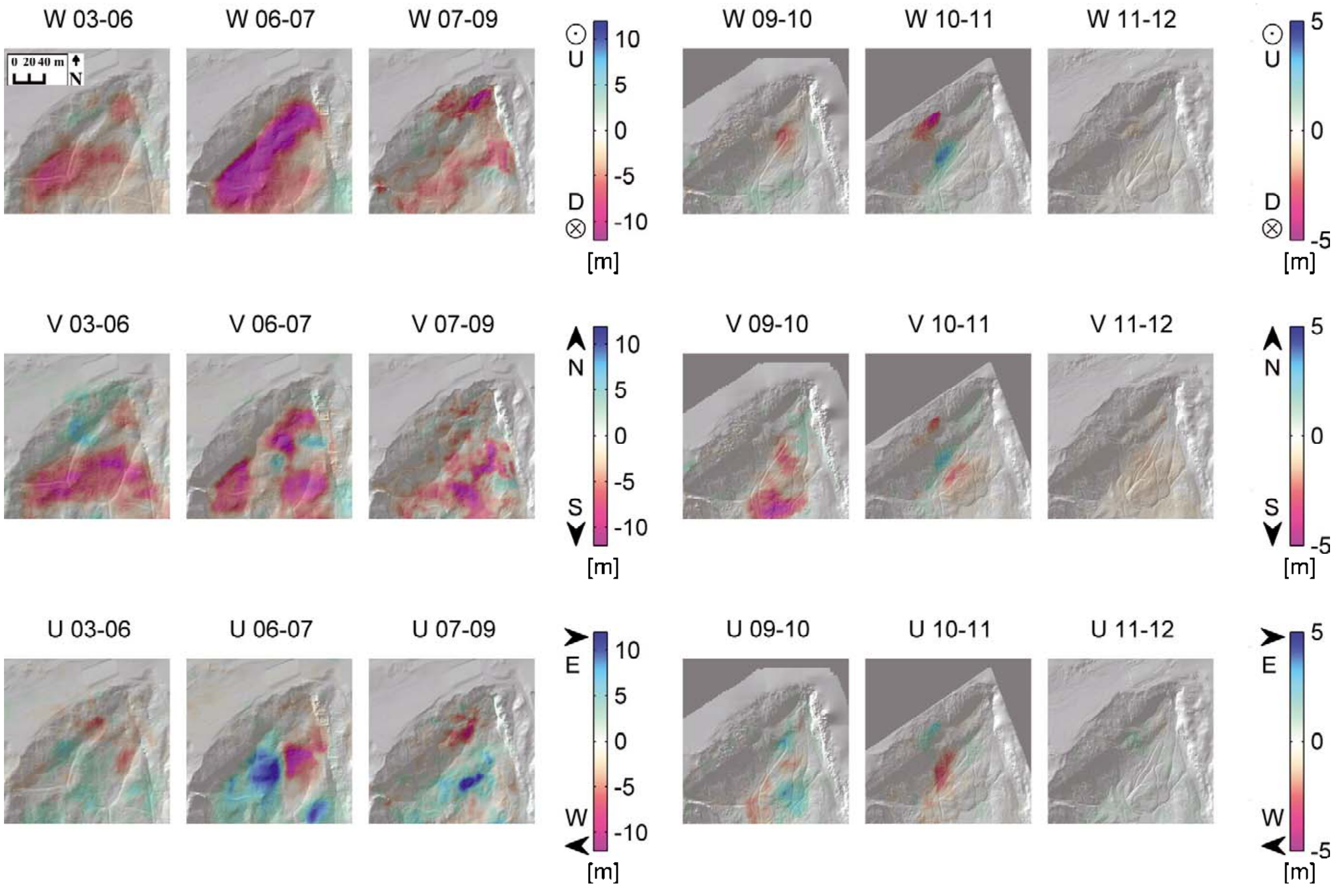


Fig. 35. Evolution of the landslide scarp. Calculated velocity vectors of zone near the rim. In the first years the motion was considerable especially in vertical and southward sense. Later the motion decreased and only small patches moved. (GHUFFAR et al. in prep.)

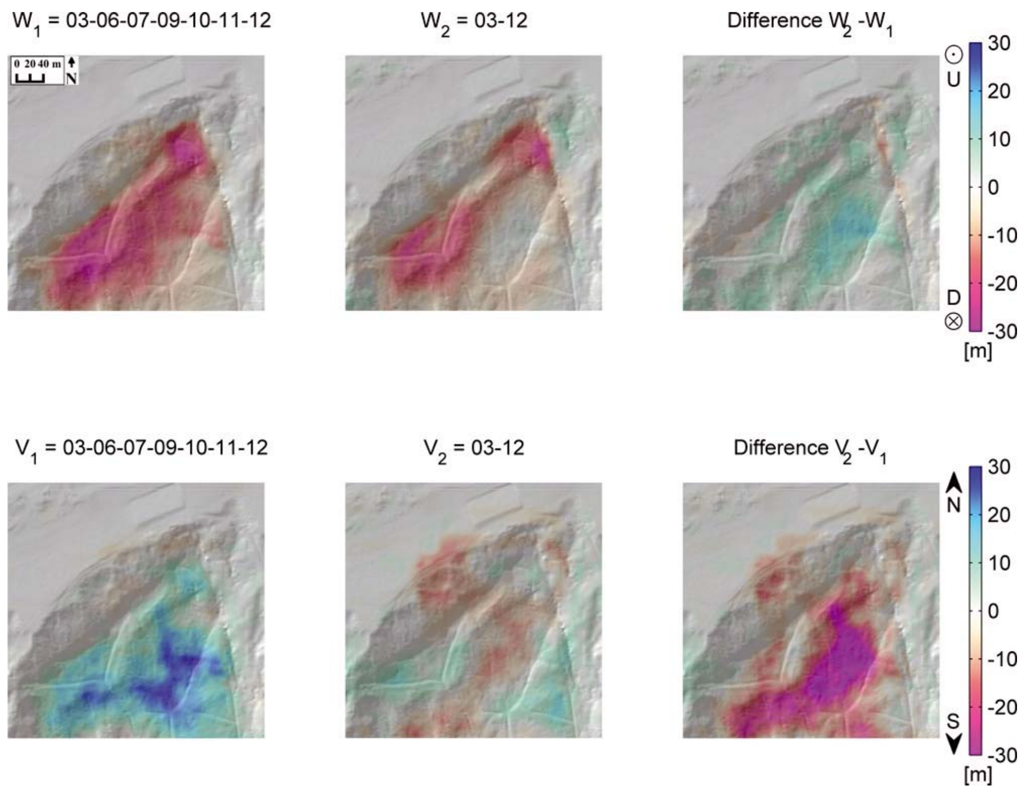


Fig. 36. Difference of the summed incremental changes (left panels) and the change between the end phase and the initial phase. The summed incremental change outpaces the end-beginning difference.

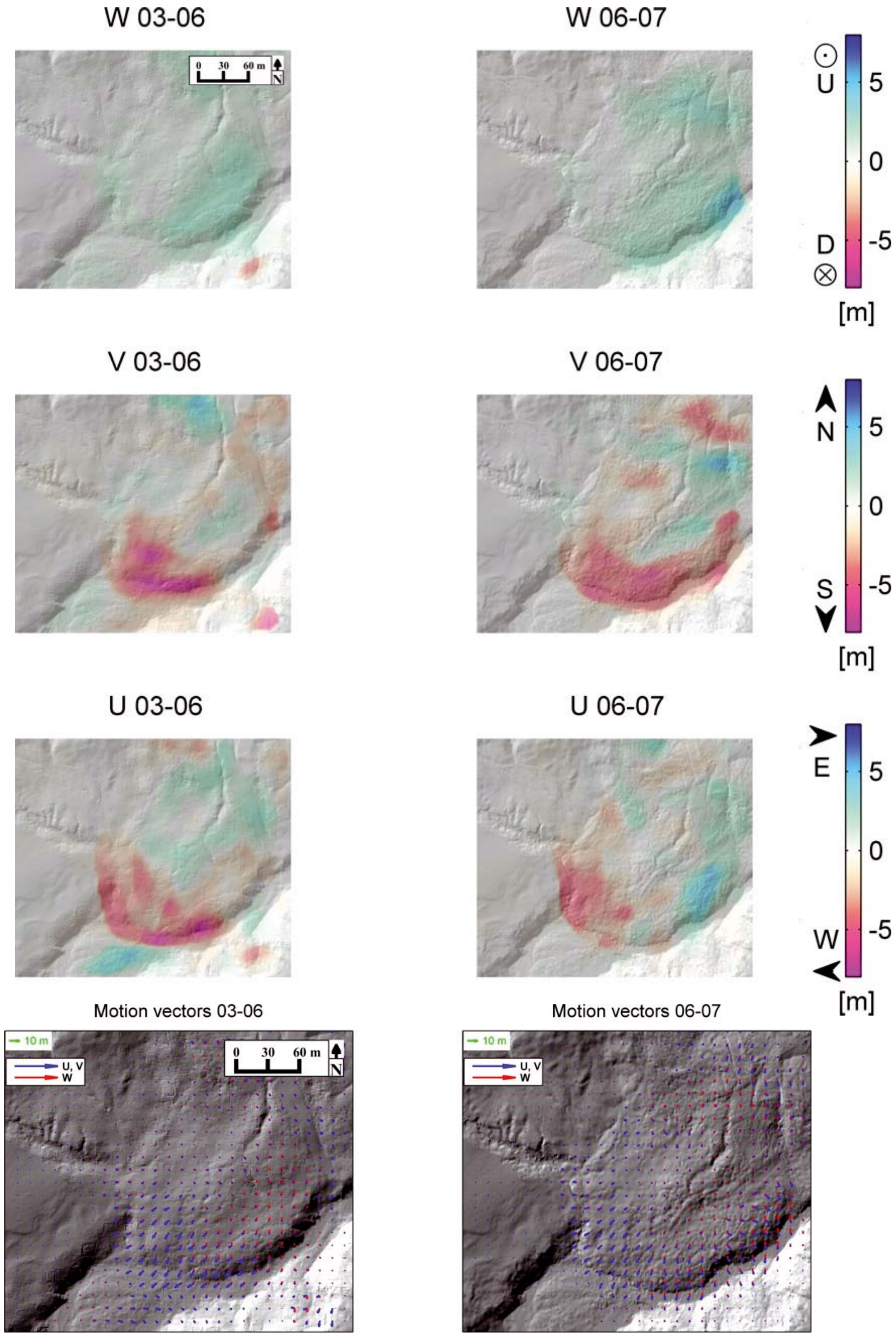


Fig. 37. The fastest moving area, the toe of the landslide. The top 6 panels map the vector components as in the previous figures. The bottom two panels show the deformation in form of vectors. Blue: actual direction, red: just the vertical component. (GHUFFAR et al. in prep.)

Among the deformation of the material, soil creep, and other mass movements a further process that has been also observed with increasing activity. In the first few years earthflows and mudflows (Fig. 38.) had negligible extent, but they have been strengthened: they increasingly characterized the eastern flank of the middle part of the landslide (the area in Fig. 34). Probably the reconstruction efforts of the dirt road going to the lower part of the landslide have also played role in inducing these small mass movements.

Fig. 38. Earthflow and mudflow in the middle part of the landslide. These phenomena appeared mostly along the dirt road where the slope was artificially steepened by some scraping activity earlier in the year. The soil was extremely highly saturated by water, and there was slow, but continuous material flow in the lower 10-20 cm.

Dissemination of results

Our dissemination concept was relatively straightforward: in the first years we intended to popularize the site and method, so the conference contributions were in the focus. As we gained experience and the gathered information increased, we moved towards written contributions.
Concerning the conference contributions the European Geosciences Union (EGU) General Assembly was found the best international possibility, furthermore, since 2002, the biannually organized conference series of Pangeo Austria developed to an international, but still Austrian scientific meeting where the audience may have interest to our activity.

Project-related contributions at the EGU General Assemblies

In order to bring Doren landslide and our laser scanning activities to the focus of the potentially interested audience and recognizing that the laser scanning was not properly represented among the sections of the General Assemblies of the European Geosciences Union (EGU), organized yearly in Vienna, we intended to establish such a session that can focus on similar experiments and measurements like our activity in Doren. EGU GA is the largest geoscientific conference in Europe, attracting 12-15 thousand contributions and over 9,000 participants. We have gradually built up our presence. First we submitted a few contributions to other (mostly geomorphological) sessions and finally we could establish a session.

The session, held first in 2009, entitled *Airborne and Terrestrial Laser Scanning and geomorphology: possibilities, problems, and solutions* was held within the Geomorphology symposia (GM1.2) and was convened by Prof. Norbert Pfeifer.
The project was represented by five poster presentations (Székely et al., Pfeifer et al., Roncat et al., and two posters by Zámolyi and Székely). Since the conveners

(including Prof. Pfeifer) intended to facilitate vivid discussion, beside of the oral contributions a time slot was allocated for a short presentation of the posters (Fig. 39).

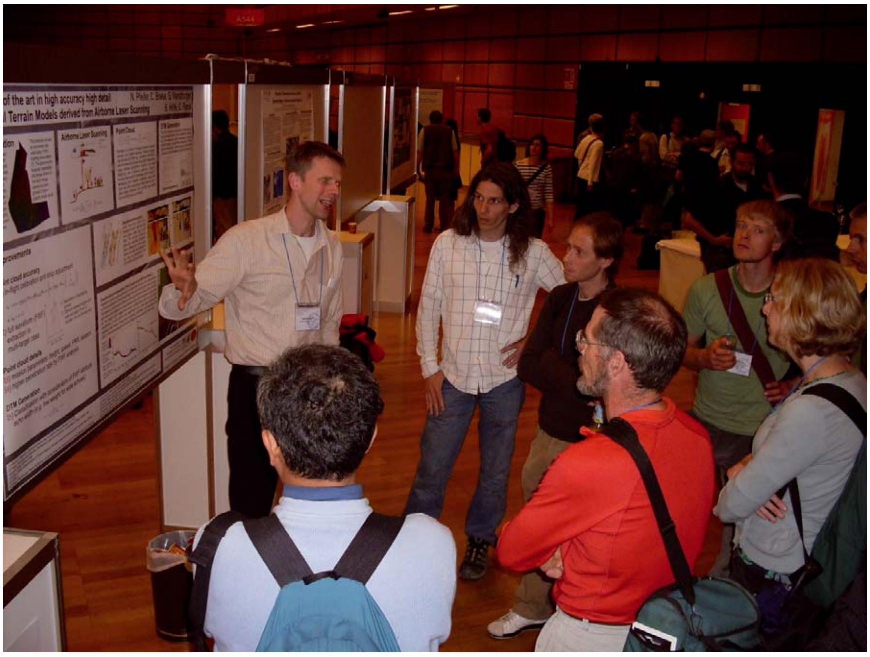


Fig. 39. Prof. Norbert Pfeifer explains his review poster to the GM1.2 session participants at EGU 2009 in Austria Center Vienna.

In 2010 the session (with the same title) was convened by B. Székely and co-convened by Prof. N. Pfeifer and Prof. B. Höfle, and our project was represented by four poster contributions (Zámolyi et al., Roncat et al., Dorninger et al., and Székely). In 2011 the structure of the sessions changed somewhat, therefore the session has been merged with other similar sessions. The merged session was convened by J. Hillier, and was entitled GM2.2/NH10.3/PS10.2 *Digital Landscapes: From Laser Scanning and High-resolution Measurement Technologies to Quantitative Interrogation of Geomorphic Processes.* The project was represented by one poster (Roncat et al.)

From 2012 a major change happened, the session has been moved to another main branch, and was entitled ESSI1.6 *Laser Scanning: 3D Spatial Data, Analysis, and Infrastructures in Geosciences*. Three project-related posters were presented (Koma et al., Ghuffar et al. and Dorninger et al.). For the next year we also intend to keep the new position and structure of the session.

Fig. 40. Prof. Norbert Pfeifer and Prof. Bernhard Höfle preparing for the ESSI 1.6 session in 2012.

Project-related poster presentations at EGU 2009:

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PFEIFER, N., BRIESE, C., MANDLBURGER, G., HÖFLE, B., RESSL, C.: State of the art in high accuracy high detail DTMs derived FROM ALS. *Geophys. Res. Abstr.* **11**: 4540. http://meetingorganizer.copernicus.org/EGU2009/EGU2009-4540.pdf

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Project-related poster presentations at EGU 2010:

DORNINGER Peter, SZÉKELY Balázs, ZÁMOLYI András, NOTHEGGER Clemens: Automated detection of geomorphic features in LiDAR point clouds of various spatial density. *Geophys. Res. Abstr.* **12**: 13613. http://meetingorganizer.copernicus.org/EGU2010/EGU2010-13613.pdf

RONCAT Andreas, DORNINGER Peter, MELZER Thomas, MOLNÁR Gábor, PFEIFER Norbert, SZÉKELY Balázs, ZÁMOLYI András, DREXEL Peter: Effect of the acquisition geometry of Airborne and Terrestrial Laser Scanning on high-resolution outlining of microtopographic landforms. *Geophys. Res. Abstr.* **12**: 15115. http://meetingorganizer.copernicus.org/EGU2010/EGU2010-15115.pdf

SZÉKELY Balázs, DORNINGER Peter, FABER Robert, NOTHEGGER Clemens: Do we need a voxel-based approach for LiDAR data in geomorphology? *Geophys. Res. Abstr.* **12**: 14528. http://meetingorganizer.copernicus.org/EGU2010/EGU2010-14528-1.pdf

ZÁMOLYI András, SZÉKELY Balázs, BISZAK Sándor: Assessing the accuracy of the Second Military Survey for the Doren Landslide (Vorarlberg, Austria). *Geophys. Res. Abstr.* **12**: 9974. http://meetingorganizer.copernicus.org/EGU2010/EGU2010-9974.pdf

ZÁMOLYI András, SZÉKELY Balázs, MOLNÁR Gábor, RONCAT Andreas, DORNINGER Peter, POCSAI Angelika, WYSZYŃSKI Marek, DREXEL Peter: Comparison of LiDAR-derived directional topographic features with geologic field evidence: a case study of Doren landslide (Vorarlberg, Austria). *Geophys. Res. Abstr.* **12**: 9875. http://meetingorganizer.copernicus.org/EGU2010/EGU2010-9875.pdf

Project-related poster presentations at EGU 2011:

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KOMA, Zsófia, POCSAI, Angelika, SZÉKELY, Balázs, DORNINGER, Peter, ZÁMOLYI, András, RONCAT, Andreas: Analysis of multitemporal laserscanned DTMs of an active landslide (Doren, Western Austria) using a robust planefitting segmentation. *Geophys. Res. Abstr.* **14**: 9742. http://meetingorganizer.copernicus.org/EGU2012/EGU2012-9742.pdf

Presentations at other conferences

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Székely B, Hollaus M., Zámolyi A., Draganits E., Roncat A., Pfeifer N. (2008): Some geoscientific applications of Airborne Laser Scanning DTMs in Austria. *Journal of Alpine Geology* **49**:109-110.

PANGEO Austria 2012 (Salzburg):

GHUFFAR S, SZÉKELY B, PFEIFER N, RONCAT A (2012): Visualisation of landslide deformation directions using range flow motion constraint applied on LiDAR data. In: FRIEDL G, STEYRER H (eds.): Pangeo Austria 2012: Abstracts, pp. 49-50.

SZÉKELY B, RONCAT A, ZÁMOLYI A, PFEIFER N, KOMA Z, DORNINGER P, MOLNÁR G, DREXEL P. (2012): Change detection of the Doren landslide using repeated terrestrial laser scanning. In: FRIEDL G, STEYRER H (eds.): Pangeo Austria 2012: Abstracts, p. 132.
http://www.uni-salzburg.at/pls/portal/docs/1/1955177.PDF

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DORNINGER P, SZÉKELY B., ZÁMOLYI A., RONCAT A. (2011): Automated detection and interpretation of geomorphic features in LiDAR point clouds. *Österreichische Zeitschift für Vermessung und Geoinformation* **99**:(2) pp. 60-69.
http://www.ovg.at/uploads/media/02_dorninger-Szekely-zamolny-roncat_.pdf

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ISBN:978-961-254-185-9

RONCAT, Andreas, DORNINGER, Peter, MOLNÁR, Gábor, SZÉKELY, Balázs, ZÁMOLYI, András, MELZER, Thomas, PFEIFER, Norbert, DREXEL, Peter (2010): Influences of the acquisition geometry of different Lidar techniques in high-resolution outlining of microtopographic landforms. In: MARSCHALLINGER, Robert, WANKER, Willi, ZOBL, Fritz (eds.): Beiträge zur COGeo 2010: Fachtagung Computerorientierte Geologie – COGeo 2010. Arbeitsgruppe Computerorientierte Geologie der Österreichischen Geologischen Gesellschaft, Salzburg, pp. 1-17.
http://dx.doi.org/10.5242/cogeo.2010.0008

Planned activities and outlook

For the next phases we plan a number of activities.
In the following spring (2013) we would like to organize a *combined measurement campaign* using parallel measurements of TLS and UAV-based high-resolution photogrammetry. The goal with this type of data fusion is (1) compare the two DTMs derived from the two dataset (2) those places where the TLS was not successful in the data acquisition because of the uncooperative geometry, the UAV imagery may complement the data set (at the toe of the landslide).
In terms of *publication*, we intend to publish the results of the 3D range flow algorithm (Ghuffar et al. 2012) presented in previous section. We also plan a comprehensive volume about our activities. We also plan to continue and extend the plane fitting analysis for most of the non-vegetated areas and relate the results to other geological observations. An analysis will be carried out to bracket the most important a-priori parameters for the processing, most prominently the standard deviation threshold. Of course, further publications are planned on this topic (following Dorninger et al. 2010). We would like to share our experience about the comparative techniques, filtering out of the vegetation points and motion detection. We also try to improve the georeference of the point clouds despite the poor visibility of the retroreflectors.
We intend to continue the measurements and we will apply for other sources of funding.

Conclusions

As it was demonstrated above, our project has resulted in a wealth of data and a lot of experience. Among them there is experience in the measurement technique, in the use of various terrestrial scanners, in the data processing, data fusion, motion detection and also some theoretical considerations. The main conclusions can be summarized as follows.

1. At the beginning of the project measurement and processing technique was just about or somewhat below the necessary accuracy to achieve the original goals, so the research question was relevant. Our measurements and experiments showed that the inaccuracies of the georeferencing, the yearly changing coverage, point density and the continuous movements, deformations of the material together causes serious co-georeferencing problems. The simple comparison of interpolation of surfaces is not a real solution if the point density (a) is not homogeneous (b) not dense enough to cancel out problems caused by the potential local artefacts of interpolation techniques.
2. The data acquisition with higher point density is necessary even if the data will be later decimated, because the decimation can be carried out in a Cartesian coordinate system, whereas the data acquisition is in a polar coordinate system. The reduction of the size of the point cloud should be achieved so that the nearest vicinity of the scanner station point should not be scanned, and not via the reduction of the point density.
3. Our results of various kinds support the hypothesis that (a) the Doren landslide has been active at least for the last two centuries with various rates of activity (b) according to structural geological measurements carried out in the surrounding areas of the landslide is probably tectonically related, possibly tectonically preformed.
4. Comparison of interpolated DTMs out of various laser scanned point clouds found to be partially applicable in change detection of deformation. Several factor may play a role in that circumstance: (a) the vegetated areas in the different epochs will differently mapped as the vegetation also changes with deformation, (b) due to the deformation or other changes the TLS station points often has to be changed, therefore the local point densities vary very strongly (c) calculation of simple difference between the DTMs of various epochs often cannot reveal the real deformation processes because the deformation is typically mixed with erosion, short-time mass movements and calculation artefacts may also affect the difference images.
5. Data fusion of remote sensing data acquired by emerging technologies as UAV-borne photogrammetric devices, or UAVs capable carrying lightweight laser scanners acting as elevated TLS station points may solve aforementioned problems. Timely and spatially dense data acquisition and appropriate data fusion may improve the georeferencing of the elevation models, less dependent on the interpolation technique. This could pave the way to gather information that is suitable for automated detection of local displacement, deformation using techniques that are already available e.g. in computer vision technology.

The various types of experience that resulted from the current project allow the formulation of some conclusions for the continuation of the activities. These can be categorized concerning

- the data acquisition
- the data management in the full-waveform analysis and
- the morphotectonic analysis.

For the *data acquisition* the main conclusions are that for areas partly covered by coniferous forests, in case of conventional (non-FWF) TLS (1) the data density must be increased (smaller angular spacing), and (2) closely spaced multiple scan positions should be applied. The application of a less dense scanning for overview scans can only be verified for non-FWF scanning, if the shape and height of the vegetation is also relevant for the project.

It is, in general, an important lesson about the data acquisition of natural hazard objects. Originally we intended to detect fault motion as well, and so far it was found not feasible, because the co-georeferencing has a comparable error. It is to expect that the georeference and therefore the co-georeference will improve in the following years (e.g. through multiple data acquisitions, various methods, etc) and then this goal becomes achievable- .
On the other hand, an important result is that the processing chain from the data acquisition to the final DTM generation (e.g., interpolation) has to be considered as a dynamic process, not a stationary, off-the-self solution. It is possible that in the foreseeable future there will be turnkey solution, but currently there might be necessary to redesign the whole process customized to the new setting found on the spot.

Concerning the *data management* of full-waveform data the main conclusion is that the last three echo method provides often unsatisfying results for our purposes therefore it seems to be necessary to analyse the real full wave data, and thus extracting more echoes that are possibly not captured by the automated method built in the instrument. Furthermore, unlike in the case of airborne FWF processing, the currently available processing techniques for FWF TLS data is cumbersome, and it is very difficult to establish a well-defined, automated processing chain.

The Doren scan campaign data also showed that if the bare soil surface is predominantly present in the area to be scanned and there is a possibility to scan the surface from two considerably differing positions and from opposing angles, the resulting point clouds can deliver a robust DTM.
However, if the scanner positions are relatively far away from each other, the resulting point clouds may contain so much internal shadowed areas that there is hardly any overlap between the data. If the area is heavily vegetated, it is possible that even in the overlapping areas there is no matching point because the self-shadowing caused by the trees is so strong, that hardly any ground surface point or patch exist that could be used to control the matching.

For the *morphotectonic studies* there are some preliminary conclusions as well.

First of all we can conclude that the adaptation of the building modelling technique, i.e. plane extraction, in this field seems to be working. Furthermore we can state that, concerning the Doren landslide scarp, the surface fitting in most of cases is successful, and there is a feasible threshold in the standard deviation that can be applied to get meaningful results. Last but not least, the (non-dense) vegetation is very successfully filtered out automatically during the processing.
Unfortunately, it must be also mentioned, that for heavily vegetated areas the algorithm cannot work, because there is no enough points from the ground surface that are required by the algorithm. (In this case the algorithm tends to find planar patches in the crown of the trees that in case of coniferous trees is often successful.)

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The project benefited of the help of great number of people and organizations. Here we provide a potentially incomplete list of them.
First of all the financing organization, Österreichische Akademie der Wissenschaften (ÖAW, Austrian Academy of Sciences) is acknowledged, as the main financial source of the project for all the years. We are very much indebted to Dr. Günter KÖCK (ÖAW), leader of the research projects and our contact person at ÖAW for his continuous support, flexibility and patience. His helpful approach and information provided helped us to complete the duties of the project.
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Peter DREXEL (Landesvermessungsamt Feldkirch, Vorarlberg, Austria) played a key role in the initiation of the project providing us with the ALS data of landslide Doren and later he continuously supported our activity.

We are thankful to the following persons

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- Guido FLATZ, the mayor of Doren was always interested in our results and the land owners of the measured areas who tolerated our activity and helped us during the measurements.
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- A great number of colleagues, students, doctoral students (who became later colleagues) have participated in the field work. Dávid BERKECZ, Ana ĐURIČIČ, Judit GÁL, Márton KEMÉNY, Andrea RAVELOSON, Michael VETTER, Martin WIESER for their help in carrying out the measurements.

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We are indebted to Petra LOIBL for seamless management of the financial aspects of the project.

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Appendix A

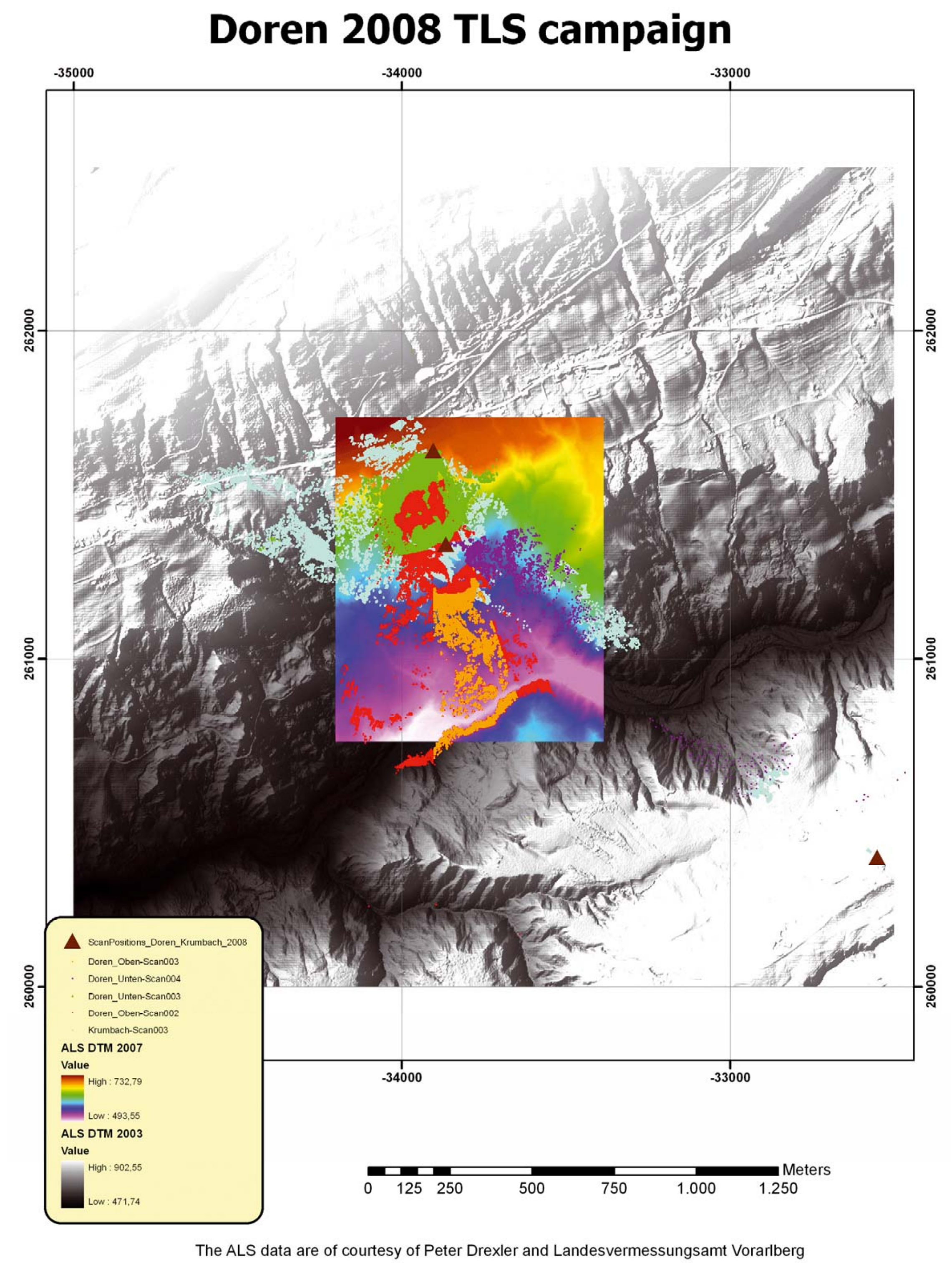

Fig. A1. The point clouds (plotted in various colours) of the Doren measurement site from 3 points. Shaded relief is an ALS DTM measured in 2003, the coloured overlay is an ALS DTM measured in 2007.

Appendix B

Fig. B1. The DTM generated from the point clouds of 2008 campaign. Resolution: 1 m. (Cf. Figs.B2-B5 and A1) Note the large area with smoothed surface; that is due to the very low point density in that regions (see coverage in Fig. A1) .

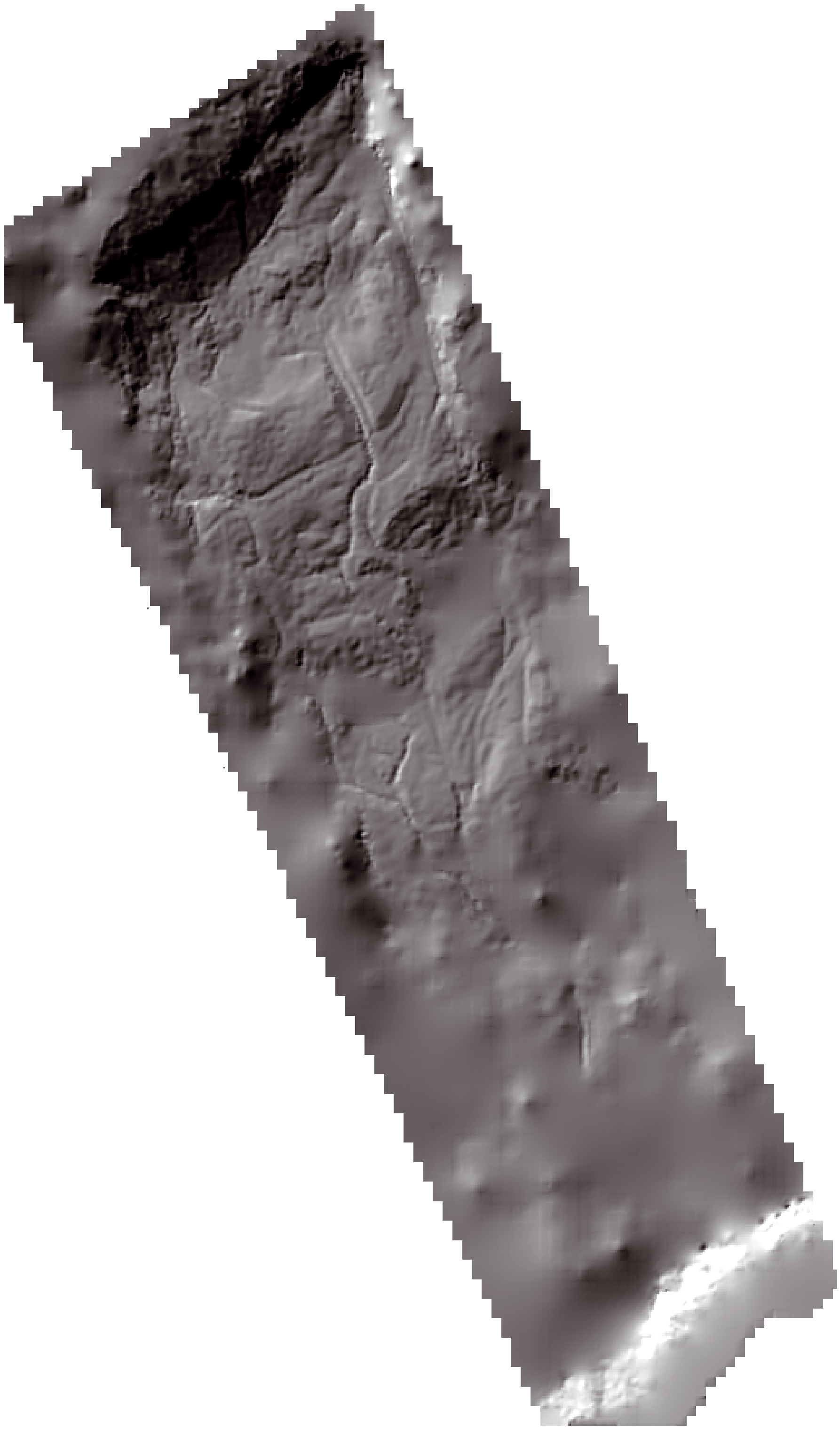

Fig. B2. The shaded DTM of the interpolated point clouds of 2009 measurements. Original resolution: 0.25 m.(Cf. Figs B1, B3-B5.)

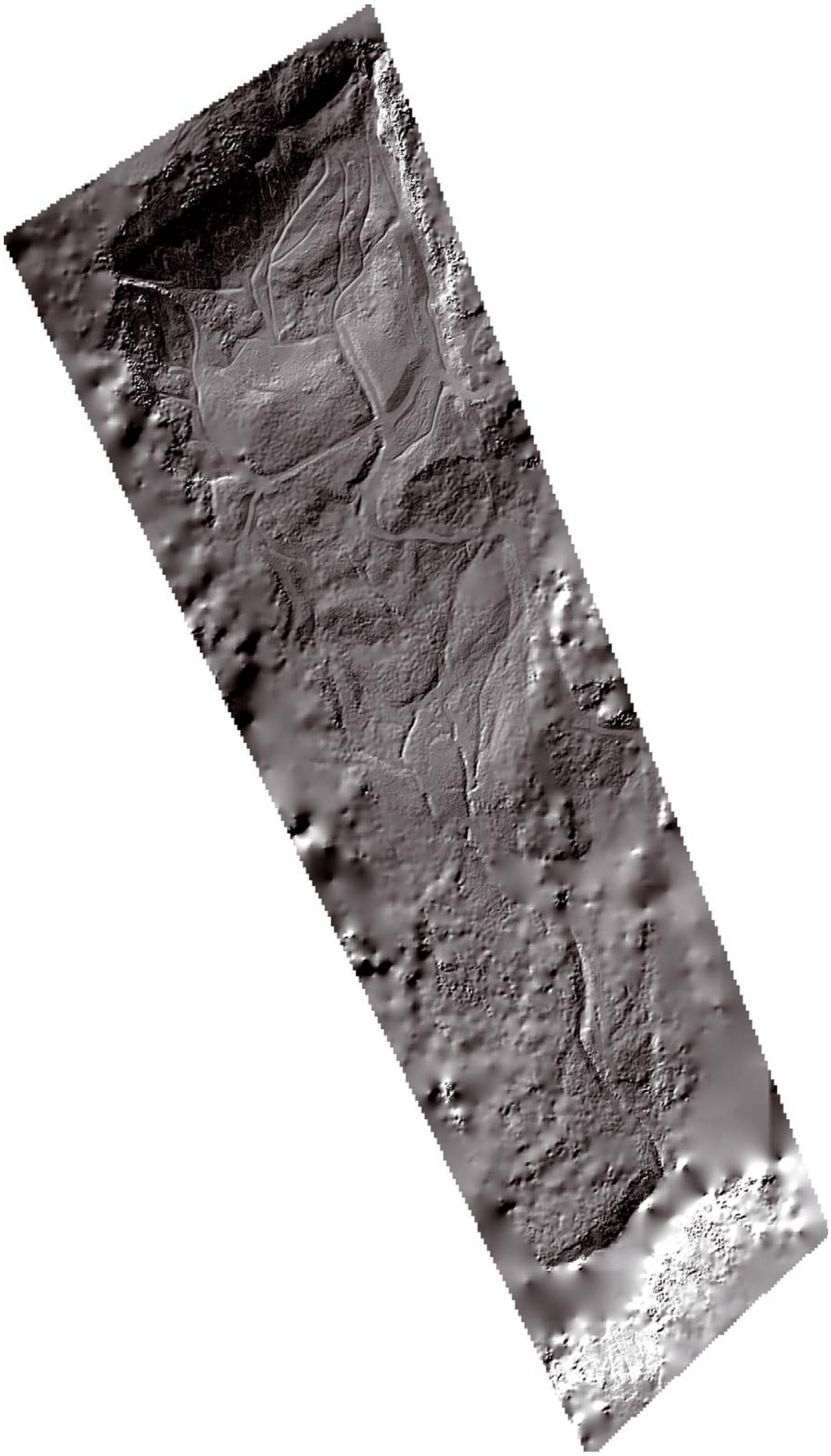

Fig. B3. The interpolated shaded DTM of the point clouds of 2010. Original resolution: 0.20 m. (Cf. Figs. B1, B2, B4, B5.)

Fig. B4. The DTM generated from the point clouds acquired in 2011. Shaded relief has 0.20 m resolution. Note the smoothed artifacts where there was not enough scan points due to the dense vegetation. . Original resolution: 0.20 m. (Cf. Figs. B1-B3, B5.)

Fig. B5. Interpolated shaded DTM of 2012 campaign. Original resolution: 0.20 m. (Cf. Figs. B1-B5.)

Appendix C

Fig. C1. A coloured rendering of the classified point cloud. View towards ENE.